Exploring subluminous X-ray binaries

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Introduction

Halfway the twentieth century, technological developments made it possible to carry detection instruments outside the absorbing layers of the Earth’s atmosphere onboard rockets and satellites. This opened up the opportunity to detect the emission from celestial objects at X-ray wavelengths, thereby providing a window to study high energy phenomena in the Universe (Giacconi 2003). The first X-ray source to be discovered outside the Solar system was Scorpius X-1, now known to be a member of a class of objects referred to as X-ray binaries. These are stellar binary systems in which a gravitationally collapsed object, either a neutron star or a black hole, consumes matter from its companion star. X-ray binaries provide a unique probe to test the laws of physics under extreme conditions, a basic quest of science. Neutron stars are a pure marvel representing matter at supra-nuclear densities in the presence of vigorous magnetic fields: conditions that are unattainable in laboratory experiments on Earth. Equally exciting, black holes form the ultimate testbeds for Einstein’s theory of General Relativity.

Although constituting the brightest X-ray point sources observed in our Galaxy, X-ray binaries can actually be observed over a wide range of luminosities. Early X-ray missions allowed only the study of the most luminous X-ray sources, but instruments have increased in sensitivity by orders of magnitude over the past decades. Owing to their high spatial resolution and sensitivity, the current generation of X-ray imaging instruments carried onboard the satellites Chandra, XMM-Newton and Swift provide an unprecedented deep view of the X-ray sky. This thesis is devoted to exposing the properties of X-ray binaries at low luminosities, which have long been inaccessible due to limitations of X-ray instruments. In this introductory chapter I discuss different phenomena that are observed at low luminosities, covering accretion outbursts and thermonuclear events occurring at low mass-accretion rates, as well as the crust cooling of neutron stars once the accretion has come to a halt.
1 Introduction

Figure 1.1: Artist impression of a low-mass X-ray binary. This image was produced using the \texttt{animation} software distributed by R. Hynes.

1.1 X-ray binaries

Unlike our Sun, most of the stars in our Galaxy are not single, but are instead part of a binary system in which two stars orbit a common centre of mass under the influence of their mutual gravitational force. If the binary constituents are close enough, the stars can exchange matter and via this interaction they can drastically influence each others evolution. If one of the components is a neutron star or a black hole, the gravitational energy release due to the in-fall of matter towards the compact primary makes the system shine in X-rays. Conservation of angular momentum prevents that matter is transferred directly from the companion onto the compact star, and the process of accretion therefore generally involves the formation of an accretion disc (see Figure 1.1). Within the disc, half of the liberated gravitational energy is converted into kinetic energy, whereas the other half is thermalized and radiated in the form of X-rays. If the accreting body is a neutron star, the kinetic energy can also be radiated at X-ray wavelengths, once the matter hits the stellar surface. However, in case of a black hole the energy can be carried beyond the event horizon without being radiated.

Based on the nature of the donor star, two types of X-ray binaries are distinguished. High-mass X-ray binaries (HMXBs) contain a massive star with $M_{\text{donor}} \gtrsim 10 \, M_\odot$ and spectral type O or B. In such a configuration the compact primary is typically capturing matter from a circumstellar disc or the strong stellar wind of its massive companion. Low-mass X-ray binaries (LMXBs), on the other hand, harbour
1.1 X-ray binaries

Companion stars with $M_{\text{donor}} \lesssim 1 \, M_\odot$ and a spectral type later than B. Such low-mass stars have very weak stellar winds and matter transfer usually takes place because the donor star overflows its Roche-lobe; the volume of space surrounding the star, within which co-rotating matter is gravitationally bound to it (see Figure 1.1). Ultra-compact X-ray binaries (UCXBs) form a subclass of LMXBs, in which the orbital period is $\lesssim 80$ min. This requires the donor star to be depleted of hydrogen in order to fit within such a tight orbit (Nelson et al. 1986).

The radiation emitted by X-ray binaries is proportional to the amount of fuel transferring onto the compact object, which can be expressed in terms of the mass-accretion rate $\dot{M}$, typically given in units of g s$^{-1}$ or $M_\odot$ yr$^{-1}$. Matter moving into the gravitational potential well of a neutron star or black hole can, if all liberated energy is converted into radiation, give rise to an accretion luminosity of $L_{\text{acc}} = G M \dot{M} / R$, where $G$ is the gravitational constant and $M$ and $R$ are the mass and radius of the compact object, respectively. In some areas of research (e.g., the study of thermonuclear bursts, see Section 1.3) the accretion luminosity is often quoted as a fraction of the Eddington limit. This represents the luminosity for which the gravitational pull of the accreting body balances the radiation pressure generated in the accretion process. For a steady, spherically symmetric accretion flow consisting of pure hydrogen gas, the Eddington luminosity is given by $L_{\text{EDD}} = 4 \pi G M m_p c / \sigma_T \approx 1 \times 10^{38} \left( M / M_\odot \right) \, \text{erg s}^{-1}$, with $m_p$ being the proton mass, $\sigma_T$ the Thompson cross-section for electron scattering and $c$ the speed of light. If the Eddington limit is exceeded, the outward force of the generated radiation overcomes the gravitational attraction, thereby putting a halt to the accretion. For a canonical neutron star with $M = 1.4 \, M_\odot$ and $R = 10$ km, the mass-accretion rate associated with this threshold is $\dot{M}_{\text{EDD}} \approx 1 \times 10^{-8} \, M_\odot \, \text{yr}^{-1}$.

1.1.1 Long-term variability in X-ray binaries

When the accretion flow in an X-ray binary is continuous, the system displays a relatively steady X-ray luminosity and is denoted as persistent. However, in many X-ray binaries mass is being transferred primarily during outburst episodes that have a typical duration of weeks to months, whereas most of the time is spent in a quiescent state during which accretion is strongly reduced and correspondingly the X-ray luminosity is a factor $\gtrsim 100$ lower. This transient behaviour is illustrated by Figure 1.2, which shows long-term lightcurves of three different X-ray binaries. As demonstrated by this image, the duration and recurrence time of accretion outbursts widely varies amongst sources. Whereas the majority of X-ray transients are active for a few weeks or months, at most, there exists a subclass of systems that undergo prolonged accretion episodes that endure for years or even decades (Wijnands 2004). An example of such a quasi-persistent X-ray binary is shown in the bottom plot of Figure 1.2.
1 Introduction

In wind-fed HMXBs, transient behaviour can be caused by clumpy or anisotropic winds (e.g., Kaper et al. 1993; Sidoli 2009). Furthermore, members of the subclass of Be/X-ray binaries can be transient due to variability in the mass loss of the Be star, or if the compact primary is in a wide and eccentric orbit, such that accretion only takes place around periastron passage (e.g., Negueruela 2004). For LMXBs, transient cycles are explained in terms of a thermal-viscous instability that causes the disc to oscillate between a cold, neutral state (quiescence), and one in which it is hot and ionised, causing a strong increase in the mass-accretion rate and resulting in an X-ray outburst (e.g., King & Ritter 1998; Lasota 2001). During quiescence, the disc regains the mass that was lost during the outburst and the cycle repeats.

1.1.2 Very-faint X-ray binaries

X-ray binaries can be further classified based on their observed 2–10 keV peak luminosities. The temporal and spectral properties of the brightest galactic X-ray binaries, which have accretion luminosities of $L_X \sim 10^{36–39}$ erg s$^{-1}$ in the 2–10 keV energy band, are well established through the work of numerous past and present X-ray missions. However, it has been realised that there exists a population of very-faint X-ray binaries that never become bright and manifest themselves with much lower
accretion luminosities of $L_X \sim 10^{34-36}$ erg s$^{-1}$ (e.g., Wijnands et al. 2006a; Campana 2009). Their identification as accreting binary systems has been established by the detection of thermonuclear X-ray bursts (in ’t Zand et al. 1991; Cocchi et al. 1999; Cornelisse et al. 2002; Del Santo et al. 2007b; Degenaar et al. 2010a) or coherent X-ray pulsations (e.g., Masetti et al. 2007; Kaur et al. 2010). In addition, there are a number of unclassified subluminous X-ray sources for which the spectral properties and energies involved in their outburst phenomena are also suggestive of an X-ray binary nature (e.g., Muno et al. 2005b; Degenaar & Wijnands 2009, 2010).

Considering that the radiation emitted by X-ray binaries is proportional to the mass-accretion rate, the observed low luminosities suggest that these systems harbour slowly accreting compact objects. The rate at which matter is transferred is a driving parameter for many phenomena related to X-ray binaries and observations of very-faint objects allow us to probe a relatively unexplored regime of accretion. For instance, the mass-accretion rate averaged over a time scale of thousands of years plays an important role in the evolution of the binary. Some very-faint X-ray sources have unusually low inferred mass-accretion rates, posing challenges to explain their existence without having to invoke exotic evolutionary scenarios (e.g., King & Wijnands 2006; Degenaar & Wijnands 2009). Furthermore, several X-ray binaries accreting at low rates have displayed thermonuclear bursts with unusual properties, which are a unique probe of how matter accumulates on the surface of a neutron star and can even provide insight into the interior properties of the neutron star (e.g., Cornelisse et al. 2002; in’t Zand et al. 2005b; Peng et al. 2007; Cooper & Narayan 2007; Degenaar et al. 2010a).

1.1.3 Monitoring the central part of our Galaxy

The high stellar density within several degrees around Sgr A*, the dynamical centre of our Galaxy, make this an ideal place to search for X-ray binaries. The field has been amongst the privileged targets of many X-ray missions and this has resulted in the identification of more than a dozen transient and persistent (candidate) X-ray binaries (e.g., Muno et al. 2009). Interestingly, there appears to be an overabundance of subluminous X-ray sources in the central regions of our Galaxy (e.g., Muno et al. 2005b; Wijnands et al. 2006a; Degenaar & Wijnands 2009, 2010). Repeated observations of this sky area hold good potential to refine our understanding of the nature and behaviour of transient low-luminosity X-ray sources.

In the past years, several programs have been launched aiming to study the population of X-ray binaries located in the vicinity of Sgr A*. Starting in 2006 February and continuing into 2010, the Swift satellite has been targeting this area with the onboard X-ray telescope. In this campaign, short ($\sim 1$ ks) observations are carried out on a nearly-daily basis, covering a field of approximately $26 \times 26$ arcmin around...
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Sgr A* (Kennea & The Swift/XRT team 2006; Degenaar & Wijnands 2009, 2010). Furthermore, an extensive campaign joining forces of Chandra and XMM-Newton was carried out between 2005 and 2008, during which the central 1.2 square degree of our Galaxy was targeted on 10 different epochs (Wijnands et al. 2006a, Chapter 7). Finally, a region subtending many square degrees has been regularly scanned by RXTE starting in 1999 (Swank & Markwardt 2001) and by Integral since 2005 (Kuulkers et al. 2007c). All this provides an ideal setting to spot transient events in one of the most active X-ray regions in the Milky Way.

1.2 Interior properties of neutron stars

1.2.1 Neutron star structure

The current consensus is that a neutron star is composed of three main regions: the atmosphere, the crust and the core (see Figure 1.3). The neutron star atmosphere is a thin (∼0.1 – 10 cm) layer consisting of ionised nuclei and non-degenerate electrons. The atmosphere accounts for a negligible fraction of the total stellar mass, but plays an important role in shaping the thermal photon spectrum emerging from the neutron star surface. A simple blackbody does not provide an adequate description, because the opacity of the atmosphere is strongly dependent on the photon frequency (e.g., Zavlin et al. 1996). Due to a steep temperature gradient, this causes high-energy photons to escape from much hotter atmospheric layers than low-energy photons. Fitting the spectra with a simple blackbody may therefore overestimate the effective temperature and in turn underestimate the emitting region (Rutledge et al. 1999).

The crust typically takes up about one tenth of the neutron star radius and can be subdivided into an inner and an outer part. The outer crust extends from the bottom of the atmosphere to the neutron drip density, \( \rho_{\text{drip}} \approx 4.3 \times 10^{11} \, \text{g cm}^{-3} \). In this region, matter consists of ions and relativistic, degenerate electrons. Due to a rise in electron Fermi energy with increasing density, the nuclei are enriched by neutrons due to inverse \( \beta \)-decay. At the base of the outer crust, neutrons become so numerous that they start to drip out of the nuclei. The inner crust covers the region from the neutron drip density to approximately the nuclear density, \( \rho_0 \approx 2.8 \times 10^{14} \, \text{g cm}^{-3} \). The inner crust is composed of electrons, free neutrons and neutron rich nuclei. Atomic nuclei begin to dissolve and merge together around the crust-core interface.

The core constitutes the largest part of the neutron star, containing approximately 99% of the total mass, and may also be subdivided into an outer and an inner part. The outer core occupies the density range \( \rho_0 \leq \rho \leq 2\rho_0 \) and can be several kilometres.

\(^1\text{Note that during the months November–February the Galactic centre is virtually unobservable due to close proximity (within 45 degrees) of the Sun.}\)
1.2 Interior properties of neutron stars

Figure 1.3: Schematic representation of the interior of a neutron star.

in depth. In this density range, matter consists mainly of degenerate neutrons and merely a few percent of protons and electrons. Due to the growing Fermi energies of the particles with increasing density, it may become energetically favourable for other particles to occur, besides the standard composition of protons, neutrons and electrons (e.g., hyperons, pions/kaons or deconfined quarks). Moving into the inner core of the neutron star, the density rises beyond $\rho \approx 2 \rho_0$ and may become as high as $\rho \approx (10 - 15) \rho_0$. The composition of the central region of the neutron star is largely unknown and the reliability of theoretical models decreases with increasing density.

1.2.2 Thermal evolution of neutron stars

Neutron stars are born extremely hot in supernova explosions, with interior temperatures around $T \sim 10^{12}$ K. During their life, neutron stars loose energy, both by the emission of neutrinos in various particle interactions, and by thermal photon emission from the surface. Since neutron stars do not burn nuclear fuel in their interior, they cannot compensate for these energy losses, and consequently they cool in time (unless accretion takes place, see below). Neutrinos are generated in numerous reactions in the neutron star interior and can freely escape the star, thereby providing an efficient source of cooling. Already within a day, the temperature in the central
1 Introduction

Figure 1.4: Theoretical cooling curves for different neutron star core compositions. The models are compared with observations of isolated neutron stars from which thermal surface emission is observed and for which ages can be estimated. Image from Yakovlev & Pethick (2004).

region of the neutron star will have dropped down to $\sim 10^9 - 10^{10}$ K.

The most dominant neutrino emission processes take place in the stellar core, where matter consists of free neutrons, protons, electrons and possibly different forms of exotic matter (see Section 1.2.1). The rate of neutrino emissions depends on the equation of state of cold nuclear matter and the central density of the neutron star. With increasing density the threshold for more efficient neutrino emission processes opens up and consequently the more massive a neutron star, the faster it is expected to cool (e.g., Yakovlev & Pethick 2004; Page et al. 2006). This is illustrated by Figure 1.4, which shows different possible thermal histories, or cooling curves, for isolated neutron stars. If thermal emission from the neutron star can be observed and its age can be estimated, e.g., via an associated supernova remnant, theoretical cooling curves can be compared with observations in order to explore the interior properties of the neutron stars.

The process of accretion significantly alters the thermal evolution of a neutron star. Under the weight of matter accumulating onto the neutron star surface, the crust is compressed thereby inducing a series of electron captures, neutron emissions and pycnonuclear fusion reactions (e.g., Haensel & Zdunik 2008). Most of the heat energy is released by processes occurring deep in the inner crust, close to the crust-
core boundary (see Figure 1.3), and is subsequently spread over the neutron star via thermal conduction. When accretion is ongoing, the thermal emission emerging from the neutron star surface is completely overwhelmed by the X-rays generated in the accretion disc (except in the case of a type-I X-ray burst, see Section 1.3). However, during the quiescent episodes of transient X-ray binaries, thermal surface emission can potentially be observed.

1.2.3 Quiescent emission of transientsly accreting neutron stars

The quiescent X-ray spectra of neutron star transients are observed to consist of one or two components: a soft, thermal component ($kT_{bb} \sim 0.1 - 0.2$ keV), and/or a hard tail that dominates the spectrum above $\sim 2$ keV. The non-thermal component is usually well-fitted by a simple powerlaw with photon index 1–2. The fractional contribution of the hard tail to the total 0.5–10 keV X-ray flux widely varies amongst sources and possibly also with changing luminosity (Jonker 2008). The physical process that is responsible for the powerlaw spectral component remains elusive (e.g., Campana 2003), but the soft emission component is most often interpreted as thermal surface radiation from the cooling neutron star.

In approximately ten thousand years, the neutron star core reaches a thermal steady state in which the heating due to the accretion of matter is balanced by cooling via neutrino emissions from the stellar core and photon radiation from the surface. This yields an incandescent emission from the neutron star surface that is set by the time-averaged accretion rate of the system, as well as the dominant neutrino cooling mechanism (e.g., Brown et al. 1998). When combined with estimates of the outburst history, observations of quiescent neutron stars can constrain the rate of neutrino emissions, thereby providing insight into the interior properties of the neutron star, in similar fashion to what is done for isolated neutron stars (see Figure 1.5).

1.2.4 Neutron star crust cooling

Once the steady state is reached, the neutron star core temperature does not change appreciably during a single outburst. However, the temperature of the crust can be dramatically altered. In regular transients that have a typical outburst duration of weeks to months, the crustal heating processes only cause a slight increase in the crust temperature (Brown et al. 1998). However, in quasi-persistent X-ray binaries the prolonged accretion episodes can cause a significant temperature gradient between the neutron star crust and core. Once the accretion ceases, the crust is expected to thermally relax on a time scale of years, until equilibrium with the core is re-established (Rutledge et al. 2002b). During the initial stages of the quiescent phase the thermal emission is therefore dominated by the cooling crust, whereas eventually
1 Introduction

Figure 1.5: Theoretical cooling curves for different neutron star core compositions compared with measurements of (or upper limits on) the quiescent thermal emission and time-averaged mass-accretion rate of a number of neutron star X-ray transients. The data points indicated by letters concern accreting millisecond pulsars. Image from Heinke et al. (2009b).

a quiescent base level is reached that is set by the thermal state of the core (Wijnands et al. 2001; Rutledge et al. 2002b). This provides the special opportunity to separately probe the properties of the neutron star crust (e.g., Brown & Cumming 2009).

In 2001, the neutron star X-ray binaries KS 1731–260 and MXB 1659–29 both made the transition to quiescence, following accretion episodes of 12.5 and 2.5 years, respectively (Wijnands et al. 2001, 2002a, 2003, 2004; Cackett et al. 2006, 2008a, 2010a). Both systems were subsequently monitored with Chandra and XMM-Newton, which revealed that the thermal flux and neutron star temperature were gradually decreasing over the course of years. This can be interpreted as cooling of the neutron star crust that has been heated during the prolonged accretion outburst. Successful modelling of the observed quiescent X-ray lightcurves with neutron star thermal evolution models supports this hypothesis and provides important constraints on the crust properties, such as the thermal conductivity and distribution of heat sources (Shternin et al. 2007; Brown & Cumming 2009). More recently, another two neutron star X-ray binaries have been monitored in their transition from outburst to quiescence. In 2007, the ~ 1.6-year long outburst of XTE J1701–462 came to a halt (Altamirano et al. 2007; Homan et al. 2007; Fridriksson et al. 2010), and in 2008 the activity of EXO 0748–676 ceased after more than 24 years (Degenaar et al. 2009, 2010d).
1.3 Thermonuclear X-ray bursts

One of the phenomena that testifies to the presence of a neutron star in an X-ray binary are type-I X-ray bursts; intense flashes of X-ray emission resulting from runaway thermonuclear burning of hydrogen (H) and/or helium (He) on the surface of accreting neutron stars. They are characterised by blackbody emission with a peak temperature of $kT_{bb} \sim 2 - 3$ keV and typically show a fast rise followed by a slower decay phase. The observational properties (e.g., duration, radiated energy and recurrence time) of type-I X-ray bursts depend on the conditions in the ignition layer, such as the temperature, thickness and hydrogen abundance. These can drastically change as the mass-accretion rate onto the neutron star varies, such that there exist distinct accretion regimes giving rise to X-ray bursts with different characteristics (Fujimoto et al. 1981; Bildsten 1998).

1.3.1 Nuclear burning regimes

Matter that accumulates onto the surface of a neutron star undergoes thermonuclear fusion reactions. The heat that is released in these processes is transported out of the burning layer by radiative cooling. A higher temperature generally increases the energy generation due to nuclear burning, which also increases the cooling rate. A thermonuclear runaway occurs when an enhanced heating rate cannot be compensated by cooling of the layer. This gives rise to a type-I X-ray burst that briefly outshines the X-ray emission coming from the accretion disc. The stability criteria depend on the temperature dependence of the nuclear burning reactions. If the temperature dependence is strong, a small increment in temperature can lead to a huge increase in the energy generation rate, causing thermonuclear runaway.

Theoretically, accretion rates near the Eddington limit are expected to maintain the temperature in the accreted envelope at high enough values for both H and He burning to proceed in a stable manner. No type-I X-ray bursts are therefore observed. For mass-accretion rates between $\sim 3 - 100\%$ of Eddington, He burning is predicted to be unstable and ignite in a H-rich environment, producing a mixed H/He burst with a duration of $\sim 10 - 100$ s. For lower rates ($\sim 0.5 - 3\%$ of the Eddington rate), H will be depleted from the burning layer before He ignites. These pure He bursts are shorter, with a typical duration of $\sim 5 - 10$ s.\(^2\) For the lowest accretion rate regime (below $\sim 0.5\%$ of Eddington), the temperature in the envelope becomes so low that H itself burns unstably. The resulting weak H-flashes can trigger two different types of He bursts (see Section 1.3.2).

All of the above types of X-ray bursts have been observed, although there are discrepancies between the theoretically predicted boundaries of the different regimes.

\(^2\)H-rich bursts are longer due to prolonged nuclear burning via the rapid proton (rp) process.
1 Introduction

and those implied by observations (e.g., van Paradijs et al. 1988; Cornelisse et al. 2003). It is important to note that the local mass-accretion rate, generally expressed as $\dot{m}$ and given in units of g s$^{-1}$ cm$^{-2}$, may differ from the global mass-accretion rate (i.e., averaged over the entire neutron star surface) if the accretion is not spherically symmetric. This may be the case, for example, when the accretion stream is confined to the magnetic poles.

1.3.2 Intermediately-long X-ray bursts

Although it had long been realised that H would burn unstably for low mass-accretion rates, it was not immediately clear what would happen upon H ignition. The discovery of a group of X-ray bursters that were accreting at low luminosities (Cornelisse et al. 2002), motivated recent theoretical work on this subject (Peng et al. 2007; Cooper & Narayan 2007). These studies have shown that for the lowest mass-accretion rates, the rise in temperature following a H flash is high enough to trigger He ignition giving rise to a mixed H/He burst. However, there exists a narrow range, spanning only a factor of a few in mass-accretion rate, in which the H flashes are not energetic enough to immediately trigger a He burst (Peng et al. 2007). As a result, a large layer of He develops, which upon ignition gives rise to an unusually energetic and long (tens of minutes in duration) He burst (Cooper & Narayan 2007). Despite the fact that the recurrence times of these events are thought to be long (on the order of a year) rendering them rare events, a few intermediately-long X-ray bursts have been observed that likely originate from the described mechanism (Chenevez et al. 2007; Falanga et al. 2009; Linares et al. 2009b; Degenaar et al. 2010a).

Type-I X-ray bursts of similar duration and comparable energy output have been observed from UCXBs, in which the mass-donating star is believed to be H-depleted, so that the neutron star accretes nearly pure He (e.g., in’t Zand et al. 2005a, 2008; Falanga et al. 2008; Kuulkers et al. 2010). In the absence of H, the temperature in the accreted envelope will be low and consequently a large layer of He can accumulate before ignition is established. Regardless of the composition of the accreted material, the intermediately-long He bursts bring about some exciting opportunities to study the neutron star properties. Whereas for regular type-I X-ray bursts the temperature at the base of the ignition layer is largely set by the burning of He (and H) itself, for very low mass-accretion rates the thermal structure of the accreted envelope becomes sensitive to the heat flux emerging from the neutron star crust (Cumming et al. 2006; Peng et al. 2007). That, in turn, depends on the interior properties of the neutron star, such as the amount of heat released due to compression of the crust by the accretion of matter, as well as the rate of core neutrino cooling (see Section 1.2). The observational progress on intermediately-long type-I X-ray bursts has opened up a new window to study the behaviour of matter under extreme density and pressure.
conditions, complementary to studies of isolated neutron stars and accreting neutron stars in quiescence.

1.4 X-ray facilities

The work presented in this thesis focuses on the properties of (candidate) X-ray binaries at low luminosities, often located in crowded regions of sky. Out of all X-ray instruments that are currently in orbit, only those onboard Chandra, XMM-Newton and Swift provide the required sensitivity and spatial resolution to perform such studies. Each of these three observatories has its own strengths and weaknesses, and the instrument of choice depends on the science case. Amongst the three, XMM-Newton has by far the largest collective area and provides the best quality spectra for active X-ray sources. On the other hand, Chandra would be the primary tool for obtaining accurate positional information, given its unprecedented sub-arcsec resolution. Furthermore, it is the favoured instrument for studying transient systems in their quiescent state, owing to its low X-ray background. Finally, the niche of Swift is its flexibility; it is the only instrument with rapid ToO response that can accommodate a large number of short, pointed observations, making it an ideal tool for monitoring observations. Regardless of the choice of instrument, this thesis focusses on spectral analysis (i.e., decomposing the detected emission into different energy bands) to study the long-term variability of X-ray sources. The following sections briefly review the instruments that were used in this work.

1.4.1 Swift

The Swift satellite is a multi-wavelength observatory launched in 2004, that is dedicated to the study of gamma-ray bursts (GRBs). However, its flexibility and X-ray sensitivity also render it a very valuable tool to study X-ray binaries. For example, the onboard Burst Alert Telescope (BAT; Barthelmy et al. 2005) can serendipitously detect X-ray bursts (e.g., in’t Zand et al. 2008; Linares et al. 2009b; Wijnands et al. 2009). The BAT is sensitive in the 15–150 keV energy range and detects randomly occurring energetic events in its wide field of view (2 steradians). The spacecraft automatically slews towards the location of the BAT trigger within tens of seconds so that follow-up observations with the narrow-field X-ray Telescope (XRT; Burrows et al. 2005) and UltraViolet/Optical Telescope (UVOT; Roming et al. 2005) can be performed.

The XRT has an effective area of $\sim 110 \text{ cm}^2$ at 1.5 keV and is sensitive in the 0.2–10 keV energy range. When operated in the photon counting (PC) mode, a two dimensional image is obtained of $\sim 23 \times 23$ arcmin providing an angular resolution of $\sim 3 - 5$ arcsec, which can be used to obtain position and spectral information for
Introduction

all the sources within the field of view. In the windowed timing (WT) mode, the CCD columns are collapsed and only the central 200 (out of 600) pixels are read out. This results in a one dimensional image with a frame time of 1.7 ms. To prevent heavy pile-up, count rates above $\sim 1.0$ counts s$^{-1}$ cause an automated shift of the PC to the WT mode.

The UVOT has a field of view of $17 \times 17$ arcmin, slightly smaller than the XRT, and can localise sources with an angular resolution of $\sim 1 – 2$ arcsec. It can be operated using the following filters: V (5000-6000 Å), B (3800-5000 Å), U (3000-4000 Å), UVW1 (2200-4000 Å), UVM2 (2000-2800 Å), UVW2 (1800-2600 Å) and the broadband white filter ($\sim 1500 – 8500$ Å). Although the sources studied in this thesis are typically highly absorbed, depriving us of a view of their UV/optical counterpart, Chapter 4 discusses observations of an unusual type-I X-ray burst that was captured simultaneously by the XRT and UVOT instruments. This allowed for an unambiguous identification of the optical counterpart and a refinement of the source location that was invaluable for further follow-up observations.

1.4.2 Chandra

The Chandra observatory became operative in 1999 and is equipped with the High Resolution Camera (HRC; Kenter et al. 2000) and Advanced CCD Imaging Spectrometer (ACIS; Garmire et al. 2003). The HRC provides the largest field of view ($\sim 30 \times 30$ arcmin) and highest spatial resolution of the Chandra instruments. It has an effective area of 225 cm$^2$ at 1 keV and is designed for imaging observations, whereas its energy resolution is poor. The ACIS detector is sensitive in the 0.1–10 keV passband and has an effective area of $\sim 340$ cm$^2$ at 1 keV. It covers a field of view of $\sim 16 \times 16$ arcmin and is designed for spectral studies.

1.4.3 XMM-Newton

Launched in 1999, XMM-Newton carries onboard the European Photon Imaging Camera (EPIC), which consists of one PN (Strüder et al. 2001) and two MOS (Turner et al. 2001) detectors that are sensitive in the 0.1–15 keV range and have spectral imaging capabilities. The relatively wide field of view ($\sim 30 \times 30$ arcmin) and large collective area ($\sim 1100$ cm$^2$ at 1 keV) of the EPIC instruments make XMM-Newton an excellent facility for surveying sky regions down to relatively faint flux levels.

1.5 Summary: a guide to this thesis

The chapters of this thesis cover the different topics broadly outlined in Sections 1.1-1.3, using the X-ray facilities introduced in Section 1.4. The common denominator
of these studies is that they focus on the properties of (candidate) X-ray binaries at low X-ray luminosities.

The first part of this thesis contains two chapters that concern the quiescent phase of neutron star transients. It describes an extensive monitoring campaign using *Chandra*, *XMM-Newton* and *Swift* to follow the transition from outburst to quiescence of the quasi-persistent neutron star X-ray binary EXO 0748–676, with the aim to study the thermal evolution of the neutron star after the cessation of its 24-year long outburst. Chapter 2 presents the first observational results obtained within 5 months after the transition towards quiescence commenced. A combined set of multiple *Chandra* and *Swift* observations showed no significant thermal evolution and several explanatory scenarios were invoked. Chapter 3 reports on continued X-ray observations of this source, using *Chandra*, *Swift* and *XMM-Newton*, now covering the first 1.6 years of the quiescent phase. The extended monitoring reveals clear evidence for a cooling neutron star crust, albeit that the shape of the decay curve is markedly different from three other quasi-persistent X-ray binaries that were monitored during their decay into quiescence. This puts constraints on the temperature of the neutron star in EXO 0748–676, which appears to be relatively hot, and on the duty cycle of the system. The latter is required to be high in order to be able to maintain the core at the high temperature inferred from observations.

Chapter 4 forms a transition in this thesis, bringing together the physics of neutron stars and actively accreting binaries. It presents the detection of an intermediately long type-I X-ray burst and multi-wavelength follow-up campaign of the previously unclassified X-ray source 1RXJ173523.7–354013. The detection of a strong ~ 2-hr long type-I X-ray burst identified the system as a neutron star LMXB and the optical/infrared follow-up observations revealed that it harbours an H-rich donor. This makes it the first unambiguous example of an intermediately-long burst that is likely triggered by weak H-flashes. An interesting challenge posed by this conclusion is how the system can be large enough to harbour a H-rich donor and at the same time remain persistent at the observed low mass-accretion rate (~ 0.1% of Eddington), apparently avoiding the thermal-viscous instability that would be expected to render the system transient.

The last part of this thesis consists of three chapters that deal with X-ray monitoring observations of a region of ~ 0.5 – 1 square degree around Sgr A*, aiming to study the spectral and long-term variability of transient X-ray sources located in this area. Chapters 5 and 6 discuss the results of a nearly-daily monitoring campaign of the central ~ 26 × 26 arcmin of our Galaxy, carried out with *Swift*XRT between 2006–2009. During these 4 years, a total of 8 different transients were observed in an active state, two of which were newly discovered X-ray sources. The long-term lightcurves obtained for the transients show that several systems undergo low-level
accretion activity that is intermediate between quiescence and their typical outburst luminosities. Finally, Chapter 7 summarises the results from monitoring observations carried out with *Chandra* and *XMM-Newton* between 2005 and 2008, covering an area of 1.2 square degree around Sgr A*. A total of 10 different X-ray sources were found active during this campaign. One of the serendipitous results of this study was the detection of a type-I X-ray burst pair from the known neutron star transient SAX J1747.0–2853. The time elapsed between the two bursts was merely 3.8 min, which is unusually short. Such events are rarely seen and pose an interesting challenge for theoretical burst models. The time interval between the bursts is too short to explain the second burst as being due to the ignition of a freshly accreted layer of material, and suggests that part of the initial fuel must be preserved after the first burst ignites.
**Chandra** and **Swift** observations of the quasi-persistent neutron star transient EXO 0748–676 back to quiescence


**Abstract** – The quasi-persistent neutron star X-ray transient and eclipsing binary EXO 0748–676 recently started the transition to quiescence following an accretion outburst that lasted more than 24 years. We report on two Chandra and twelve Swift observations performed within five months after the end of the outburst. The Chandra spectrum is composed of a soft, thermal component that fits to a neutron star atmosphere model with $kT_{\infty} \sim 0.12$ keV, joined by a hard powerlaw tail that contributes $\sim 20\%$ of the total 0.5–10 keV unabsorbed flux. The combined Chandra/Swift data set reveals a relatively hot and luminous quiescent system with a temperature of $kT_{\infty} \sim 0.11 - 0.13$ keV and a bolometric thermal luminosity of $\sim 8.1 \times 10^{33} - 1.6 \times 10^{34} \ (D/7.4 \text{ kpc})^2 \text{ erg s}^{-1}$. We discuss our results in the context of cooling neutron star models.
2.1 Introduction

Neutron star X-ray transients spend the vast majority of their time in quiescence, in which they are dim with typical luminosities of $\sim 10^{32-34}$ erg s$^{-1}$, but occasionally show an immense X-ray brightening in which their luminosity can rise to levels of $\sim 10^{36-38}$ erg s$^{-1}$ (e.g., Chen et al. 1997). Their quiescent X-ray spectra are observed to consist of one or two components: a soft, thermal component ($kT \sim 0.1-0.2$ keV), and/or a hard powerlaw tail (dominating above 2 keV, photon index $\Gamma \sim 1-2$; e.g., Asai et al. 1996).

Several explanations have been put forward to describe the quiescent emission of neutron star transients, such as low-level accretion (e.g., Zampieri et al. 1995; Menou et al. 1999) or emission mechanisms connected to the magnetic field of the neutron star (see e.g., Campana 2003). However, the soft spectral component is most often interpreted as thermal emission emerging from the neutron star surface (Brown et al. 1998). During accretion outbursts, a series of nuclear reactions deposit heat in the neutron star crust (e.g., Haensel & Zdunik 1990a, 2008; Gupta et al. 2007), which spreads over the neutron star. The gained heat is radiated as thermal emission from the surface once the system returns to quiescence. In this interpretation the quiescent thermal emission depends on the time-averaged accretion rate of the system (e.g., Brown et al. 1998), as well as on the neutrino emission mechanism that operates in the core, which regulates the cooling (e.g., Yakovlev et al. 2003).

There exists a small group of quasi-persistent X-ray transients, which undergo prolonged accretion outbursts with a duration of years to decades rather than the usual weeks to months (e.g., Wijnands 2004). In these systems, the neutron star crust is substantially heated and becomes thermally decoupled from the core. Once the outburst ends, the crust will cool down primarily through heat conduction towards the core, until eventually thermal equilibrium is re-established (e.g., Rutledge et al. 2002b). This thermal relaxation depends strongly on the properties of the crust, such as the thermal conductivity.

In recent years, the quasi-persistent X-ray binaries KS 1731–260 and MXB 1659–29 have been monitored during the transition towards quiescence with Chandra and XMM-Newton following accretion outbursts with a duration of $\sim 12.5$ and $\sim 2.5$ yr, respectively (Wijnands et al. 2001, 2002a, 2003, 2004; Cackett et al. 2006, 2008a). For both systems, these observations revealed a lightcurve that decayed exponentially from a bolometric luminosity of $\sim (3 - 5) \times 10^{33}$ erg s$^{-1}$ a few months after the outburst, levelling off to $\sim (2 - 5) \times 10^{32}$ erg s$^{-1}$ several years later (Cackett et al. 2006, 2008a). Whereas the initial stages of this decaying curve are set by the properties of the crust, the quiescent base level reflects the thermal state of the core (e.g., Brown & Cumming 2009). Confronting the observed cooling curves with thermal evolution models suggests that the neutron stars in both KS 1731–260 (Shternin et al. 2007)
and MXB 1659–29 (Brown & Cumming 2009) have a highly conductive crust. This idea is supported by theoretical plasma simulations of Horowitz et al. (2007), who demonstrated that the accreted matter will arrange itself in a lattice structure with a high thermal conductivity.

### 2.1.1 EXO 0748–676

Recently, the quasi-persistent neutron star X-ray transient EXO 0748–676 also started the transition to quiescence. This low-mass X-ray binary was initially discovered with EXOSAT in 1985 February (Parmar et al. 1986), although it appears as an EXOSAT slew survey source several times before this date (Reynolds et al. 1999, the earliest detection dates back to 1984 July 15). Prior to its discovery, EXO 0748–676 was serendipitously observed with Einstein in 1980 May, from which Garcia & Callanan (1999) deduced a $kT \sim 0.2$ keV blackbody source spectrum with a $0.5–10$ keV luminosity of $\sim 5 \times 10^{33} \left( \frac{D}{7.4 \text{kpc}} \right)^2 \text{erg s}^{-1}$. The system displays X-ray dips and exhibits eclipses with a duration of $\sim 8.3$ min every $3.82$ h (Parmar et al. 1986).

Ever since its discovery, EXO 0748–676 was consistently detected with luminosities $\gtrsim 10^{36} \text{erg s}^{-1}$ by various satellites. In particular, regular monitoring with RXTE showed that the source maintained a relatively steady $2–20$ keV flux of approximately $2 \times 10^{-10} \text{erg cm}^{-2} \text{s}^{-1}$, since 1996 ($L_X \sim 1 \times 10^{36} \left( \frac{D}{7.4 \text{kpc}} \right)^2 \text{erg s}^{-1}$; Wolff et al. 2008a). However, observations with the Proportional Counter Array (PCA) obtained on 2008 August 12 signalled a decrease in $2–20$ keV source flux, down to $\sim 7 \times 10^{-11} \text{erg cm}^{-2} \text{s}^{-1}$ ($L_X \sim 5 \times 10^{35} \left( \frac{D}{7.4 \text{kpc}} \right)^2 \text{erg s}^{-1}$; Wolff et al. 2008a). This decline was confirmed when Swift observations with the X-ray Telescope (XRT) performed on 2008 September 28 found the source at a $0.5–10$ keV flux of $\sim 2 \times 10^{-12} \text{erg cm}^{-2} \text{s}^{-1}$ ($L_X \sim 1 \times 10^{34} \left( \frac{D}{7.4 \text{kpc}} \right)^2 \text{erg s}^{-1}$; see Section 2.2.2). Subsequent RXTE/PCA observations, carried out on 2008 October 5, failed to detect EXO 0748–676 (Wolff et al. 2008b), consistent with the flux level observed with Swift/XRT. Optical and near-IR observations of the optical counterpart of EXO 0748–676 (UY Vol), performed in October 2008, detected a decrease in its optical brightness compared with the active X-ray state (Hynes & Jones 2008; Torres et al. 2008).

The observed large decline in X-ray and optical luminosity suggest that EXO 0748–676 is returning to quiescence after having actively accreted for 24 yrs. With its long outburst duration, EXO 0748–676 is a good candidate to look for thermal relaxation of the accretion heated neutron star crust now that the system is returning to quiescence. In this Letter we report on Chandra and Swift observations of EXO 0748–676 performed within the first five months after the accretion outburst ceased.
2 Chandra and Swift observations of EXO 0748–676 back to quiescence

![Figure 2.1: Spectra of both Chandra observations, along with the model fit (solid line) for $D = 7.4$ kpc, $\Gamma = 1$ and $M = 1.4$ M$_{\odot}$. The dotted lines indicate the nssxmos and powerlaw components.](image)

2.2 Observations, analysis and results

2.2.1 Chandra data

As part of our Chandra Target of Opportunity (TOO) proposal EXO 0748–676 was observed with Chandra/ACIS-S on 2008 October 12–13 22:09–02:51 UTC (obs ID 9070) and on 2008 October 15 12:46–17:13 UTC (obs ID 10783), for on-source times of 13.8 and 13.3 ks, respectively. We used the CIAO tools (v. 4.0) and standard Chandra analysis threads to reduce the data. No background flares were found, so all data were used for further analysis. The ACIS-S3 CCD was operated in a 1/8 sub-array to circumvent any possible pile-up problems. For the resulting frame-time of 0.4 s and the observed fluxes (see Table 2.1), the pile-up fraction was < 4%.

Source spectra and lightcurves were extracted from a circular region with a radius of 3′′ centred on the position of EXO 0748–676. Background events were obtained from an annular region with an inner (outer) radius of 10″ (25″). The lightcurves of both Chandra observations display one eclipse at times consistent with the ephemeris of Wolff et al. (2009). During the eclipses, only one photon was detected from the source region and a similar amount was found for the normalized background. This indicates that X-rays from the neutron star are not detected during the eclipses. To calculate the correct non-eclipse time-averaged fluxes, we reduced the exposure times of the fits files by 500 s (the approximate duration of the eclipses; Parmar et al. 1986;
Table 2.1: Results from fitting the Chandra/ACIS-S spectral data.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>5.0 kpc</th>
<th>5.0 kpc</th>
<th>7.4 kpc</th>
<th>8.3 kpc</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{\text{H}}$ ($10^{22}$ cm$^{-2}$)</td>
<td>0.12 ± 0.03</td>
<td>0.12 ± 0.02</td>
<td>0.12 ± 0.02</td>
<td>0.12 ± 0.03</td>
</tr>
<tr>
<td>$kT_{\text{eff}}$ (eV)</td>
<td>112 ± 14</td>
<td>113 ± 12</td>
<td>118 ± 4</td>
<td>119 ± 4</td>
</tr>
<tr>
<td>$M_{\text{NS}}$ (M$_\odot$)</td>
<td>(1.4)</td>
<td>1.8 ± 0.4</td>
<td>(1.4)</td>
<td>(1.4)</td>
</tr>
<tr>
<td>$R_{\text{NS}}$ (km)</td>
<td>11.9 ± 2.8</td>
<td>(10)</td>
<td>17.1 ± 3.2</td>
<td>18.8 ± 3.4</td>
</tr>
<tr>
<td>$F_X$ (0.5–10 keV)</td>
<td>1.3 ± 0.1</td>
<td>1.3 ± 0.1</td>
<td>1.3 ± 0.2</td>
<td>1.3 ± 0.1</td>
</tr>
<tr>
<td>$F_X$ (0.01–100 keV)</td>
<td>1.5 ± 0.2</td>
<td>1.5 ± 0.2</td>
<td>1.5 ± 0.1</td>
<td>1.5 ± 0.2</td>
</tr>
<tr>
<td>$L_X$ (0.01–100 keV)</td>
<td>4.5 ± 0.6</td>
<td>4.5 ± 0.5</td>
<td>9.8 ± 1.0</td>
<td>10.2 ± 1.2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>5.0 kpc</th>
<th>5.0 kpc</th>
<th>7.4 kpc</th>
<th>8.3 kpc</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{\text{H}}$ ($10^{22}$ cm$^{-2}$)</td>
<td>0.14 ± 0.03</td>
<td>0.14 ± 0.03</td>
<td>0.14 ± 0.03</td>
<td>0.14 ± 0.03</td>
</tr>
<tr>
<td>$kT_{\text{eff}}$ (eV)</td>
<td>106 ± 9</td>
<td>108 ± 12</td>
<td>112 ± 8</td>
<td>114 ± 8</td>
</tr>
<tr>
<td>$M_{\text{NS}}$ (M$_\odot$)</td>
<td>(1.4)</td>
<td>2.0 ± 0.3</td>
<td>(1.4)</td>
<td>(1.4)</td>
</tr>
<tr>
<td>$R_{\text{NS}}$ (km)</td>
<td>14.0 ± 3.4</td>
<td>(10)</td>
<td>19.4 ± 4.1</td>
<td>21.3 ± 4.5</td>
</tr>
<tr>
<td>$F_X$ (0.5–10 keV)</td>
<td>1.4 ± 0.1</td>
<td>1.3 ± 0.2</td>
<td>1.3 ± 0.1</td>
<td>1.3 ± 0.1</td>
</tr>
<tr>
<td>$F_{\text{bol}}$ (0.01–100 keV)</td>
<td>1.5 ± 0.2</td>
<td>1.5 ± 0.2</td>
<td>1.5 ± 0.2</td>
<td>1.5 ± 0.2</td>
</tr>
<tr>
<td>$L_{\text{bol}}$ (0.01–100 keV)</td>
<td>4.5 ± 0.6</td>
<td>4.5 ± 0.5</td>
<td>9.8 ± 1.3</td>
<td>10.2 ± 1.6</td>
</tr>
</tbody>
</table>

Note. – The quoted errors represent 90% confidence levels and $\chi^2$ = 1.1 for all fits (173 d.o.f.). $F_X$ represents the total unabsorbed 0.5–10 keV flux, while $F_{\text{bol}}$ gives the bolometric $\text{nsatmos}$ flux (both in units of $10^{-12}$ erg cm$^{-2}$ s$^{-1}$). $L_{\text{bol}}$ is the bolometric luminosity (for the model distance) of the $\text{nsatmos}$ component in units of $10^{33}$ erg s$^{-1}$.

Wolff et al. 2009). Using the tool $\text{grppha}$ we binned the spectra to contain a minimum of 20 photons per bin.

The resulting spectra were fitted using Xspec (v. 12.0; Arnaud 1996). The Chandra observations were performed < 3 days apart, and we did not find any significant spectral changes between the two when fitting the data sets separately. Therefore, we tied all spectral parameters between the two observations. We fitted the data with a neutron star atmosphere model $\text{nsatmos}$ (Heinke et al. 2006). The normalization of this model was always fixed to one, which corresponds to the entire neutron star surface emitting. Using only the $\text{nsatmos}$ model, the data above $\sim$ 2 – 3 keV cannot be fit properly. If we add a powerlaw component, this improves a fit with the neutron star mass and radius fixed at $M_{\text{NS}} = 1.4$ M$_\odot$ and $R_{\text{NS}} = 10$ km from $\chi^2 = 217.7/174$ d.o.f. to $\chi^2 = 181.0/172$ d.o.f. (an F-test suggests a $1.3 \times 10^{-7}$ probability of achieving this level of improvement by chance). The $\text{nsatmos}$ model calculates the effective temperature in the neutron star frame. We
converted this to the effective temperature as seen by an observer at infinity according to $kT_{\text{eff}}^{\infty} = kT_{\text{eff}}(1 + z)$, where $1 + z = (1 - R_s/R_{NS})^{-1/2}$ is the gravitational redshift factor, with $R_s = 2GM_{NS}/c^2$ being the Schwarzschild radius, $G$ the gravitational constant and $c$ the speed of light.

When the neutron star mass and radius are fixed to canonical values of $M_{NS} = 1.4 \, M_\odot$ and $R_{NS} = 10 \, \text{km}$, the best-fit yields $D = 3.4_{-0.7}^{+1.4} \, \text{kpc}$, $\Gamma = 2.3 \pm 0.9$, $N_H = (0.16 \pm 0.1) \times 10^{22} \, \text{cm}^{-2}$ and $kT_{\text{eff}}^{\infty} = 100_{-23}^{+14} \, \text{eV}$. The fitted distance is lower than the best estimate of 7.4 kpc (with an allowed range of 5–8.3 kpc), which was inferred from analysis of type-I X-ray bursts (Galloway et al. 2008a, but see Galloway et al. 2008b for possible additional uncertainties). If we keep the mass and radius at canonical values and in addition fix the distance to either $D = 7.4 \, \text{kpc}$ or $D = 8.3 \, \text{kpc}$, we obtain $\Gamma < 0$. However, for $D = 5 \, \text{kpc}$ we obtain $\Gamma = 0.7_{-0.7}^{+1.6}$, $N_H = (0.10 \pm 0.01) \times 10^{22} \, \text{cm}^{-2}$ and $kT_{\text{eff}}^{\infty} = 118 \pm 2 \, \text{eV}$.

Finally, we explored fits with the distance fixed at 5, 7.4 or 8.3 kpc, but with either the mass or the radius left to vary freely (and the other kept at its canonical value). Since the powerlaw slope is not well constrained, this parameter was fixed to $\Gamma = 1$ or $\Gamma = 2$. The free parameters for each fit are then the hydrogen column density ($N_H$), the effective temperature ($kT_{\text{eff}}$), the normalization of the powerlaw component and either the mass ($M_{NS}$) or radius ($R_{NS}$).

We deduced unabsorbed fluxes in the 0.5–10 keV energy band and calculated the bolometric flux of the thermal component by extrapolating the nsarros model (using a zero normalization for the powerlaw) for the energy range 0.01–100 keV. The powerlaw contribution to the total 0.5–10 keV unabsorbed flux is $\sim 16 – 17\%$ for the fits with $\Gamma = 1$ and $\sim 19 – 20\%$ if $\Gamma = 2$. The results are summarised in Table 2.1. For $D = 7.4 \, \text{kpc}$ and $D = 8.3 \, \text{kpc}$ the fits with the radius fixed at $R_{NS} = 10 \, \text{km}$ resulted in neutron star masses of $M_{NS} > 2.5 \, M_\odot$, i.e., exceeding the causality limit of 2.23 $M_\odot$ for a neutron star radius of 10 km; these fits are not listed in Table 2.1. The spectra of both Chandra observations are plotted in Figure 2.1.

2.2.2 Swift data

In addition to the Chandra data, we obtained Swift/XRT TOO observations of EXO 0748–676 returning to quiescence (see Table 2.2 for an overview). The XRT data, collected in the photon counting (PC) mode, were processed using standard Swift analysis threads. We extracted source spectra (using Xselect v. 2.3) from a circular region with a radius of 15″, while background spectra were obtained from an annular region with an inner (outer) radius of 50″ (100″). The spectra were grouped to contain bins with a minimum number of 10 photons. We reduced the exposure times of those observations that contained eclipses according to the ephemeris of Wolff et al. (2009) to calculate the correct non-eclipse time-averaged fluxes (see Table 2.2).
2.2 Observations, analysis and results

Table 2.2: Results from fitting the Swift/XRT spectral data.

<table>
<thead>
<tr>
<th>Obs ID</th>
<th>Date</th>
<th>$t_{\text{exp}}$ (ks)</th>
<th>$kT_{\text{eff}}$ (eV)</th>
<th>$F_X$</th>
<th>$F_{\text{bol}}^\text{th}$</th>
<th>$L_{\text{bol}}$</th>
<th>$\chi^2$ (d.o.f.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>51300025</td>
<td>2008-09-28</td>
<td>0.93</td>
<td>133 ± 9</td>
<td>2.3 ± 0.6</td>
<td>16 ± 5</td>
<td>1.7 (2)</td>
<td></td>
</tr>
<tr>
<td>31272001*</td>
<td>2008-10-07</td>
<td>1.49</td>
<td>128 ± 11</td>
<td>1.9 ± 0.6</td>
<td>12 ± 4</td>
<td>0.1 (2)</td>
<td></td>
</tr>
<tr>
<td>31272003/4*</td>
<td>2008-10-29/30</td>
<td>5.01</td>
<td>119 ± 5</td>
<td>1.4 ± 0.2</td>
<td>9.4 ± 2</td>
<td>1.4 (10)</td>
<td></td>
</tr>
<tr>
<td>31272005*</td>
<td>2008-11-02</td>
<td>4.78</td>
<td>115 ± 5</td>
<td>1.1 ± 0.2</td>
<td>8.3 ± 1</td>
<td>1.4 (10)</td>
<td></td>
</tr>
<tr>
<td>31272007</td>
<td>2008-11-28</td>
<td>3.04</td>
<td>121 ± 6</td>
<td>1.5 ± 0.3</td>
<td>11 ± 2</td>
<td>1.0 (5)</td>
<td></td>
</tr>
<tr>
<td>31272008*</td>
<td>2008-12-05</td>
<td>3.40</td>
<td>122 ± 6</td>
<td>1.6 ± 0.3</td>
<td>11 ± 2</td>
<td>0.8 (6)</td>
<td></td>
</tr>
<tr>
<td>31272009</td>
<td>2008-12-20</td>
<td>4.22</td>
<td>115 ± 5</td>
<td>1.2 ± 0.2</td>
<td>8.8 ± 1</td>
<td>1.9 (9)</td>
<td></td>
</tr>
<tr>
<td>31272012</td>
<td>2009-01-10</td>
<td>3.71</td>
<td>118 ± 5</td>
<td>1.3 ± 0.2</td>
<td>9.5 ± 2</td>
<td>1.1 (7)</td>
<td></td>
</tr>
<tr>
<td>31272013</td>
<td>2009-01-16</td>
<td>4.16</td>
<td>116 ± 5</td>
<td>1.3 ± 0.2</td>
<td>9.2 ± 2</td>
<td>1.2 (8)</td>
<td></td>
</tr>
<tr>
<td>31272014</td>
<td>2009-01-23</td>
<td>1.45</td>
<td>113 ± 10</td>
<td>1.1 ± 0.4</td>
<td>8.1 ± 3</td>
<td>0.1 (1)</td>
<td></td>
</tr>
<tr>
<td>31272015*</td>
<td>2009-01-30</td>
<td>3.95</td>
<td>116 ± 5</td>
<td>1.2 ± 0.2</td>
<td>9.0 ± 1</td>
<td>0.8 (8)</td>
<td></td>
</tr>
</tbody>
</table>

Note. – The quoted errors represent 90% confidence levels. $F_X$ represents the 0.5–10 keV total model flux (described in the text) and $F_{\text{bol}}^\text{th}$ gives the 0.01–100 keV bolometric flux. Both are given in units of $10^{-12}$ erg cm$^{-2}$ s$^{-1}$. $L_{\text{bol}}$ gives the 0.01–100 keV luminosity of the nsatmos model component in units of $10^{33}$ erg s$^{-1}$ and assuming a source distance of 7.4 kpc. The exposure times of observations marked with an asterisk were corrected for (parts of) eclipses.

We fitted all grouped Swift spectra with a combined nsatmos and powerlaw model, were we fixed all parameters except the effective temperature. Different fits to the Chandra spectral data yield similar $\chi^2$ values, so there is no preferential model to use for the Swift data (see Table 2.1). We picked the fit with $D = 7.4$ kpc (the best distance estimate), $\Gamma = 1$, $M_{\text{NS}} = 1.4 M_\odot$, $R_{\text{NS}} = 17.1$ km and $N_H = 0.12 \times 10^{22}$ cm$^{-2}$. The powerlaw normalization was adjusted for each observation so that this component contributes 17% of the total 0.5–10 keV flux. To improve the statistics, we tied the spectral parameters between observations 31272003 and 31272004, which were performed only one day apart. The results are presented in Table 2.2.

Figure 2.2 displays the effective temperatures and thermal bolometric fluxes derived from the Chandra and Swift data. The Chandra observations (obtained < 3 days apart) are plotted as a single data point (with an error on the time to indicate the spread of the two observations). The Swift observations 31272003 and 31272004 are also plotted as a single point. The bottom panel displays the evolution of the effective temperature of EXO 0748–676 together with the data points and curve fits of KS 1731–260 and MXB 1659–29 (taken from Cackett et al. 2006, 2008a). Cackett et al. (2006) set the reference time, $t_0$, for KS 1731–260 and MXB 1659–29 to the day of the last detection with RXTE/PCA. For EXO 0748–676 we set $t_0$ at 2008 September 5, which is in between the last detection with RXTE/PCA (August 12) and the first Swift observation (September 28).
2.3 Discussion

We obtained two Chandra and twelve Swift observations within five months after the cessation of the very long (~24 yrs) active period of EXO 0748–676. We found (assuming a neutron star atmosphere model nsatmos) a relatively hot and luminous quiescent system with a temperature of $kT_{\text{eff}} \sim 0.11 - 0.13$ keV and a thermal bolometric luminosity of $\sim (8.1 - 16) \times 10^{33} \left(\frac{D}{7.4 \text{ kpc}}\right)^2$ erg s$^{-1}$. In addition to a soft, thermal component, the Chandra data reveal a hard powerlaw tail, which contributes $\sim 20\%$ to the total 0.5–10 keV luminosity of $8.5 \times 10^{33} \left(\frac{D}{7.4 \text{ kpc}}\right)^2$ erg s$^{-1}$.

Comparing the evolution of the effective temperature of EXO 0748–676 with that of KS 1731–260 and MXB 1659–29 (bottom panel Figure 2.2) illustrates that the current data of EXO 0748–676 is consistent with the fit through the data of MXB 1659–29 (as well as with KS 1731–260 if the temperatures would be scaled). This suggests that the neutron star crust may thermally relax in the coming years, revealing a cooling curve as has been observed for KS 1731–260 and MXB 1659–29. The current data set can then provide an unique insight into the early stages of neutron star cooling, and can possibly put constraints on the amount of heating in the outer crustal layers (Brown & Cumming 2009).

However, the top and middle panel of Figure 2.2 suggest that the effective temperature and thermal bolometric flux of EXO 0748–676 have not decreased during the past three months (see also Table 2.2). The 0.5–10 keV luminosity remains approximately constant at $L_X \sim 8 \times 10^{33} \left(\frac{D}{7.4 \text{ kpc}}\right)^2$ erg s$^{-1}$, which is close to the value deduced from an Einstein observation in 1980 (see Section 2.1.1). There are several explanations that can account for the current high luminosity of EXO 0748–676 and are consistent with the Einstein detection of EXO 0748–676 in 1980.

Firstly, we cannot exclude the possibility that we detect low-level accretion from EXO 0748–676, since the resulting radiation spectrum may have a shape similar to that expected from crustal heating (e.g., Zampieri et al. 1995). We made Fast Fourier Transforms of the Chandra data (excluding the eclipses), but did not find any variability on short time scales ($< 10^4$ s) that might indicate continued accretion (Rutledge et al. 2002a).

If the observed thermal emission is due to crustal heating, then the constant luminosity might imply that the crust and core have already reached thermal equilibrium. The neutron star in EXO 0748–676 would then be relatively hot compared to other quiescent systems (see e.g., figure 4 of Heinke et al. 2009b). Such a high quiescent luminosity can be explained by standard core cooling. Since enhanced neutrino emission mechanisms are suppressed only when the density in the core is relatively low, this scenario would imply that the neutron star in EXO 0748–676 is not very massive and has not had enough time to accrete a significant amount of matter (the exact mass limit for enabling enhanced core cooling mechanisms is model dependent).
A high time-averaged mass-accretion rate can also give rise to a high quiescent luminosity. Parmar et al. (1986) stated that between 1970 and 1980 no outburst reaching $\sim 10^{36}$ erg s$^{-1}$ was observed for EXO 0748–676 using *Uhuru, Ariel V* and *HEAO-1*, indicating that in the 10 yrs prior to the *Einstein* detection the source was in quiescence (at least, no similar long outburst as the most recent one occurred; shorter outbursts of weeks or even months cannot be excluded). Besides this, we cannot put any additional constraints on the duty cycle of EXO 0748–676. Normally, X-ray transients reside significantly longer in quiescence than in outburst, but for EXO 0748–676 the quiescence state might be similar in duration to the outburst episodes. The neutron star core temperature could then be maintained by repeated accretion episodes at a significantly higher level than would be the case if it would spend most of its time in quiescence.

Furthermore, a high quiescent luminosity can be accounted for if the neutron star crust has a low thermal conductivity, so that it will cool on a time scale of decades rather than a few years and remains hot for a long time (Rutledge et al. 2002b; Shternin et al. 2007). A drawback of this explanation is that there is no obvious reason why the neutron star in EXO 0748–676 would be so different in this respect from KS 1731–260 and MXB 1659–29, for which a low crust conductivity can be ruled out (Shternin et al. 2007; Brown & Cumming 2009). This would also oppose independent molecular dynamics simulations that predict a regular crystal lattice structure (Horowitz et al. 2007).

More *Chandra* observations of EXO 0748–676 are scheduled for this year and these will provide insight into the different scenarios discussed above.

**Acknowledgments**
We are grateful to the referee, Nathalie Webb, for very useful comments. This work was supported by NWO, the Netherlands Organization for Scientific Research. We acknowledge the use of the *Swift* public data archive. EMC was supported by NASA through the Chandra Fellowship Program. MTW, PSR and KSW acknowledge the United States Office of Naval Research. J.H. and W.H.G.L. gratefully acknowledge support from Chandra grant GO8-9045X.
Figure 2.2: Evolution of the bolometric flux (top) and effective temperature (middle/bottom) of EXO 0748–676, deduced from Chandra/ACIS-S (squares) and Swift/XRT (triangles) observations. The bottom panel displays the effective temperatures of KS 1731–260 (light grey stars; from Cackett et al. 2006) and MXB 1659–29 (dark grey bullets; from Cackett et al. 2006, 2008a), in addition to the data points of EXO 0748–676. The exponential decay fits to the data of KS 1731–260 and MXB 1659–29 are also shown (dashed and solid line, respectively).
Further X-ray observations of EXO 0748–676 in quiescence: evidence for a cooling neutron star crust


Monthly Notices of the Royal Astronomical Society in press

Abstract – In late 2008, the quasi-persistent neutron star X-ray transient and eclipsing binary EXO 0748–676 started a transition from outburst to quiescence, after it had been actively accreting for more than 24 years. In a previous work, we discussed Chandra and Swift observations obtained during the first five months after this transition. Here, we report on further X-ray observations of EXO 0748–676, extending the quiescent monitoring to 1.6 years. Chandra and XMM-Newton data reveal quiescent X-ray spectra composed of a soft, thermal component that is well-fitted by a neutron star atmosphere model. An additional hard powerlaw tail is detected that changes non-monotonically over time, contributing between 4–20% to the total unabsorbed 0.5–10 keV flux. The combined set of Chandra, XMM-Newton and Swift data reveals that the thermal bolometric luminosity fades from ~ $1 \times 10^{34}$ to $6 \times 10^{33}$ (D/7.4 kpc)$^2$ erg s$^{-1}$, whereas the inferred neutron star effective temperature decreases from ~ 124 to 109 eV. We interpret the observed decay as cooling of the neutron star crust and show that the fractional quiescent temperature change of EXO 0748–676 is markedly smaller than observed for three other neutron star X-ray binaries that underwent prolonged accretion outbursts.
3.1 Introduction

EXO 0748–676 is an intensively studied low-mass X-ray binary that was initially discovered with the European X-ray Observatory SATellite (EXOSAT) in 1985 February (Parmar et al. 1985). However, in retrospect the source already appeared active in EXOSAT slew survey observations several times beginning 1984 July (Reynolds et al. 1999), whereas the earliest detection dates back to 1980 May, when EXO 0748–676 was serendipitously observed with the Einstein satellite (Parmar et al. 1986). The system exhibits irregular X-ray dips and displays eclipses that last for ~ 8.3 min and recur every 3.82 hr, which allow the unambiguous determination of the orbital period of the binary (Parmar et al. 1986; Wolff et al. 2009).

The detection of type-I X-ray bursts (e.g., Gottwald et al. 1986) conclusively identify the compact primary as a neutron star. A few X-ray bursts have been observed that exhibited photospheric radius expansion (PRE), which indicates that the Eddington luminosity is reached near the burst peak and allows for a distance estimate towards the source (Wolff et al. 2005; Galloway et al. 2008a). For a Helium-dominated photosphere, a distance of $D = 7.4 \pm 0.9$ kpc can be derived, while assuming solar composition results in a distance estimate of $D = 5.9 \pm 0.9$ kpc (Galloway et al. 2008a). The rise time and duration of the PRE bursts observed from EXO 0748–676 suggest pure Helium ignition, rendering 7.4 kpc as the best distance estimate (Galloway et al. 2008a), although this value is subject to several uncertainties (Wolff et al. 2005; Galloway et al. 2008b).

At the time of its discovery, EXO 0748–676 was detected at 2–10 keV luminosities of $\sim (1 - 7) \times 10^{36}$ (D/7.4 kpc)$^2$ erg s$^{-1}$ (Parmar et al. 1986). However, during the Einstein observation of 1980, several years prior to the EXOSAT detections, it displayed a 0.5–10 keV luminosity of $\sim 5 \times 10^{33}$ (D/7.4 kpc)$^2$ erg s$^{-1}$ (Parmar et al. 1986; Garcia & Callanan 1999). The source can therefore be classified as a transient X-ray binary. Nevertheless, such systems typically exhibit accretion outbursts that last only weeks to months (e.g., Chen et al. 1997), whereas EXO 0748–676 was persistently detected at luminosities of $\sim 10^{36-37}$ (D/7.4 kpc)$^2$ erg s$^{-1}$ by various satellites for over 24 years. Similar prolonged accretion episodes continuing for years to decades have been observed for a few other systems, which are termed quasi-persistent X-ray binaries (e.g., Wijnands 2004).

In 2008 August–September, observations with the Proportional Counter Array (PCA) onboard the Rossi X-ray Timing Explorer (RXTE) and Swift’s X-ray Telescope (XRT) indicated that the X-ray flux of EXO 0748–676 was declining (Wolff et al. 2008a,b). Optical and near-IR observations of the optical counterpart, UY Vol, performed in 2008 October showed that the optical emission had also faded compared to the brighter X-ray state (Hynes & Jones 2008, 2009; Torres et al. 2008). These events indicated that the accretion was ceasing and that the system was tran-
3.1 Introduction

Figure 3.1: RXTE/ASM 20-day averaged lightcurve (1.5–12 keV) of EXO 0748–676, illustrating the cessation of the outburst in 2008 August/September. For reference: the dashed vertical line corresponds to 2008 December 31. The arrows indicate the times of our four sequences of Chandra observations, which were performed when the source dropped below the detection limit of RXTE (both of the ASM and the PCA).

sitioning from outburst to quiescence. This is also illustrated by Figure 3.1, which displays the X-ray lightcurve of EXO 0748–676 as observed with the All-Sky Monitor (ASM) onboard RXTE since 1996. The decrease in source activity is clearly seen around ~ 4600 days.

Chandra observations carried out in 2008 mid-October (i.e., after the transition to quiescence) revealed an X-ray spectrum composed of a soft, thermal component joined by a hard powerlaw tail that dominates the spectrum above ~ 2 – 3 keV (Dege-naar et al. 2009, see also Section 3.2.4). This is frequently seen for neutron star X-ray binaries in quiescence (e.g., Rutledge et al. 1999; in’t Zand et al. 2001; Tomsick et al. 2004). The non-thermal component is usually well-fitted by a simple powerlaw with index 1–2 (e.g., Asai et al. 1996). The fractional contribution of the hard powerlaw tail to the 0.5–10 keV X-ray flux widely varies amongst sources and possibly also with changing luminosity (Jonker et al. 2004; Jonker 2008). The physical process that is responsible for the powerlaw spectral component remains elusive (see e.g., Campana et al. 1998; Campana 2003).

Although the soft spectral component has been ascribed to low-level accretion
Neutron star crust cooling in EXO 0748–676

(Zampieri et al. 1995), it is most often interpreted as thermal surface radiation from the cooling neutron star (Brown et al. 1998). According to this model, the accretion of matter compresses the neutron star crust, which induces a series of electron captures, neutron emissions and pycnonuclear fusion reactions (e.g., Haensel & Zdunik 1990b, 2003, 2008; Gupta et al. 2007). The heat energy released in these processes is spread over the neutron star via thermal conduction.

The neutron star cools primarily via neutrino emissions from the stellar core, as well as photon radiation from the surface. The former depends on the equation of state of cold nuclear matter and the central density of the neutron star (e.g., Yakovlev & Pethick 2004; Page et al. 2006). The neutron star core reaches a thermal steady state in $\sim 10^4$ years, yielding an incandescent thermal emission from the neutron star surface set by the time-averaged accretion rate of the system, as well as the rate of neutrino emissions from the stellar core (e.g., Brown et al. 1998; Colpi et al. 2001). When combined with estimates of the outburst history, observations of quiescent neutron stars can constrain the rate of neutrino emissions, thereby providing insight into the interior properties of the neutron star (e.g., Heinke et al. 2009b).

Once the steady state is reached, the neutron star core temperature will not change appreciably during a single outburst, but the temperature of the crust can be dramatically altered. In regular transients that have a typical outburst duration of weeks to months, the crustal heating processes will only cause a slight increase in the crust temperature (Brown et al. 1998). However, in quasi-persistent X-ray binaries the prolonged accretion episodes can cause a significant temperature gradient between the neutron star crust and core. Once the accretion ceases, the crust is expected to thermally relax on a time scale of years, until equilibrium with the core is re-established (Rutledge et al. 2002b). During the initial stages of the quiescent phase the thermal emission will therefore be dominated by the cooling crust, whereas eventually a quiescent base level is reached that is set by the thermal state of the core (Wijnands et al. 2001; Rutledge et al. 2002b). This provides the special opportunity to separately probe the properties of the neutron star crust (Haensel & Zdunik 2008; Brown & Cumming 2009).

In 2001, the neutron star X-ray binaries KS 1731–260 and MXB 1659–29 both made the transition to quiescence, following accretion episodes of 12.5 and 2.5 yr, respectively (Wijnands et al. 2001, 2002a, 2003, 2004; Cackett et al. 2006, 2008a). More recently, in 2007, the $\sim 1.6$-year long outburst of XTE J1701–462 came to a halt (Altamirano et al. 2007; Homan et al. 2007; Fridriksson et al. 2010). All three systems were subsequently monitored with Chandra and XMM-Newton, which revealed that thermal flux and neutron star temperature were gradually decreasing over the course of years (see also Section 3.4). This can be interpreted as cooling of the neutron star crust that has been heated during the prolonged accretion outburst.
3.2 Observations and data analysis

Successful modelling of the observed quiescent X-ray lightcurves with neutron star thermal evolution models supports this hypothesis and provides important constraints on the crust properties, such as the thermal conductivity (Shternin et al. 2007; Brown & Cumming 2009).

Along these lines we have pursued an observational campaign of EXO 0748–676 to study the time evolution of the quiescent X-ray emission following its long accretion outburst. In Degenaar et al. (2009), we discussed Chandra and Swift observations obtained between 2008 September 28 and 2009 January 30. We found a relatively hot and luminous quiescent system with a temperature of $kT_{\text{eff}} \sim 0.11 - 0.13$ keV and a thermal 0.01–100 keV luminosity of $\sim (8 - 16) \times 10^{33} (D/7.4 \text{ kpc})^2$ erg s$^{-1}$. No clear decrease in effective temperature and thermal bolometric flux was found over the five-month time span. In this paper we report on continued Swift and Chandra observations of EXO 0748–676 during its quiescent state. In addition, we include an archival XMM-Newton observation performed $\sim$ 2 months after the cessation of the outburst. Previous Chandra and Swift observations discussed by Degenaar et al. (2009) were re-analysed in this work in order to obtain a homogeneous quiescent lightcurve.

3.2 Observations and data analysis

Table 3.1 gives an overview of all new observations of EXO 0748–676 discussed in this paper. A list of earlier Chandra and Swift observations obtained during the quiescent phase can be found in Degenaar et al. (2009).

3.2.1 XMM-Newton

EXO 0748–676 was observed with the European Photon Imaging Camera (EPIC) onboard XMM-Newton on 2008 November 6 from 08:30–16:42 UT (see also Bassa et al. 2009). The EPIC instrument consists of two MOS detectors (Turner et al. 2001) and one PN camera (Strüder et al. 2001), which are sensitive in the 0.1–15 keV energy range and have effective areas of 922 cm$^2$ and 1227 cm$^2$ (at 1 keV), respectively. Both the PN and the two MOS instruments were operated in full window mode and using the medium optical blocking filter. Data reduction and analysis was carried out with the Science Analysis Software (SAS; v. 9.0.0). We reprocessed the Original Data Files (ODF) using the tasks emproc and epproc. To identify possible periods of high particle background, we extracted high-energy lightcurves ($\geq 10$ keV for the MOS and between 10–12 keV for the PN). No strong background flares occurred during the observation. The net exposure times are 29.0 and 22.9 ks for the MOS and PN, respectively. EXO 0748–676 is detected at count rates of $0.16 \pm 0.01$ counts s$^{-1}$ (MOS) and $0.55 \pm 0.01$ counts s$^{-1}$ (PN).
Table 3.1: Observation log.

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<td></td>
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Note. – The observations marked with an asterisk contain (part of) eclipses. The listed exposure times represent the duration of the observations uncorrected for eclipses.
3.2 Observations and data analysis

Source spectra and lightcurves were obtained with the software task evselect, using a 35″ circular region and applying pattern selections 0–12 and 0–4 for the MOS and PN data, respectively. Corresponding background events were extracted from a circular region with a radius of 70″. For the MOS cameras, the background was positioned on a source-free region on the same CCD as the source. For the PN instrument, the background events were extracted from an adjacent CCD, at the same distance from the readout node to ensure similar low-energy noise. The ancillary response files (arf) and redistribution matrices (rmf) were generated for each of two MOS and the PN cameras with the tasks arfgen and rmfgen.

The EPIC lightcurves show two full eclipses (see also Bassa et al. 2009), corresponding to eclipse cycles 54384 and 54385 in the numbering system of Parmar et al. (1986). To calculate the correct non-eclipse time-averaged fluxes, we reduce the exposure times for each instrument by 500 s per eclipse, which is the approximate length of the eclipses of EXO 0748–676 (Wolff et al. 2009).\footnote{As shown by Wolff et al. (2009), the duration of the eclipses of EXO 0748–676 varied between \( \sim 484 \) and \( 512 \) s over the years 1996–2008. These small uncertainties in the eclipse duration do not affect our results.}

Using the tool grppha, the spectra were grouped to contain a minimum of 20 photons per bin.

### 3.2.2 Chandra

We obtained three new Chandra observations of EXO 0748–676 using the S3 chip of the Advanced CCD Imaging Spectrometer (ACIS; Garmire et al. 2003). The ACIS detector is sensitive in the 0.1–10 keV passband and has an effective area of 340 cm\(^2\) at 1 keV. The first observation consists of two separate exposures obtained on 2009 February 23–24 22:07–03:15 UT (obs ID 9071) and 2009 February 25 12:32–15:59 UT (obs ID 10871), lasting for \( \sim 15.8 \) and \( \sim 9.6 \) ks, respectively. In both data sets, EXO 0748–676 is clearly detected at a count rate of \( 0.17 \pm 0.01 \) counts s\(^{-1}\). This is a factor \( \sim 1.5 \) lower than observed in 2008 October, when the source was detected with Chandra/ACIS-S at a rate of \( 0.24 \pm 0.01 \) counts s\(^{-1}\). Two full eclipses are seen in the lightcurve of observation 9071, while one eclipse is present in that of 10871 (eclipse cycle numbers 55071, 55072 and 55080, respectively).

A second Chandra observation was carried out on 2009 June 10, from 12:36–21:16 UT, with an exposure time of 27.2 ks (obs ID 9072). In this observation EXO 0748–676 is detected at a count rate of \( 0.16 \pm 0.01 \) counts s\(^{-1}\) and the lightcurve shows two full eclipses (cycles 55740 and 55741). Furthermore, a 27.4 ks exposure was taken on 2010 April 20 from 02:37–11:28 UT (obs ID 11059), which captured three full eclipses (see Figure 3.2, these correspond to eclipse cycle numbers 57708, 57709 and 57710), and detected the source at a count rate of \( 0.14 \pm 0.01 \) counts s\(^{-1}\). Similar to our treatment of the XMM-Newton data, we reduce the exposure times of all
Figure 3.2: *Chandra* ACIS-S 0.5–8 keV lightcurve of EXO 0748–676 obtained on 2010 April 20 (obs ID 11059). Each point represents 200 s of data. Three eclipses are visible.

*Chandra* observations by 500 s per eclipse. There are no indications of background flares, so the full data set was used in further analysis.

We reduced the data employing the *ciao* tools (v. 4.2) and standard *Chandra* analysis threads. For all three observation sequences, the ACIS-S3 CCD was operated in a 1/8 sub-array, resulting in a frame-time of 0.4 s. For the observed count rates, the pile-up fraction is < 2%, so no further corrections were made. Spectra were extracted with the tool *psfextract*, while the rmf and arf files were created using *mkacisrmf* and *mkaarf*, respectively. We employ a circular region of 3″ to obtain source events and a 10 – 25″ annulus for the background. We also reprocessed the *Chandra* observation obtained in 2008 October (see Degenaar et al. 2009) to benefit from the calibration update that was released in 2009 December. Prior to spectral fitting, the spectra were grouped to contain at least 20 photons per bin.

3.2.3 *Swift*

In addition to the *Chandra* and *XMM-Newton* observations, we have been monitoring EXO 0748–676 on a regular basis with the XRT (Burrows et al. 2005) aboard the *Swift* satellite. The instrument has an effective area of 110 cm² at 1.5 keV and is operated in the energy range of 0.2–10 keV. Starting in 2008 late-September, ap-
proximately 2 – 3 pointings were performed each month with a typical duration of
≈ 3 – 5 ks per observation, and a separation of ≈ 1 – 2 weeks. From 2009 November
onwards, the cadence was lowered to one observation per month with a longer
exposure time when possible (see Table 3.1). EXO 0748–676 is detected in the XRT
observations at count rates of ≈ (1 – 5) × 10⁻² counts s⁻¹.

All Swift/XRT observations were obtained in the photon counting (PC) mode
and were processed using the xrtpipeline with standard quality cuts (event grade
0–12). Using XSELECT (v. 2.4), we extracted source spectra from a circular region
with a radius of 35″ (~ 15 pixels), which optimises the signal to noise ratio at the
observed count rates (Evans et al. 2007). Corresponding background events were
averaged over three source-free regions of similar shape and size. Employing the
tool xrtexpomap, we created exposure maps to account for the effective area of the
CDD, while arfs generated with xrtmkarf account for vignetting and point-spread-
function corrections. The latest rmf (v. 11) was obtained from the caldb database.

Due to low statistics, it is not possible to identify eclipses in the Swift lightcurves.
Therefore, we used the ephemeris of Wolff et al. (2009) to determine during which
observations eclipses were occurring (see Table 3.1). To calculate the correct
non-eclipse time-averaged fluxes, the exposure times of these observations were reduced
with the duration of the eclipses contained in the data (500 s if a full eclipse was
present, but less if only part of an eclipse was expected). Furthermore, Swift observa-
tions obtained within a 2-day time span were summed to improve the data statistics.²

This seems justified, since the Chandra data do not reveal any spectral changes on
such time scales (see Section 3.2.4).

### 3.2.4 Spectral models

We fitted the spectral data in the 0.5–10 keV energy range using Xspec (v. 12.0; Arnaud 1996). This software package facilitates fitting a spectral model simultaneously
to multiple data files, which each have their own response and background files. As
is common practise, we fit the XMM-Newton data with all spectral parameters tied
between the different detectors (i.e., the model parameters are not allowed to vary
independently between the PN and two MOS detectors). For all fits throughout this
paper, we included the effect of neutral hydrogen absorption, $N_H$, along the line of
sight using the phabs model with the default Xspec abundances (Anders & Grevesse
1989) and cross-sections (Balucinska-Church & McCammon 1992).

We first investigate the shape of the quiescent spectrum of EXO 0748–676 by
considering the XMM-Newton observation, which provides the highest statistics. A
single absorbed powerlaw (powelaw in Xspec) provides an acceptable fit to the data

²This is the case for obs IDs 31272037/38, 31272039/40 and 31272043/44/45; see Table 3.1.
Figure 3.3: Spectra of the Chandra observations of 2008 October (black) and 2010 April (red), along with the model fits (solid lines). The separate contributions of the nsatmos and powerlaw components are represented by the dotted (2008 data) and dashed (2010 data) lines.

\( \chi^2_v = 1.3 \) for 466 d.o.f.). However, the spectral index is unusually large for an X-ray binary (\( \Gamma = 4.7 \pm 0.1 \)) and suggests that the spectrum has a thermal shape. Using a simple absorbed blackbody model, bbodyrad, results in an adequate fit (\( \chi^2_v = 1.2 \) for 466 d.o.f.), although the inferred emitting region has a much smaller radius than expected for a neutron star (~ 2 – 4 km for distances of 5 – 10 kpc). Nevertheless, it is thought that radiative transfer effects in the neutron star atmosphere cause the emergent spectrum to deviate from a blackbody (e.g., Zavlin et al. 1996; Rutledge et al. 1999). There are several neutron star atmosphere models available within Xspec, which yield equivalent results (see e.g., Heinke et al. 2006; Webb & Barret 2007). In the remainder of this work, we concentrate on fitting the data with a neutron star atmosphere model nsatmos (Heinke et al. 2006).

The nsatmos model consists of five parameters, which are the neutron star mass and radius (\( M_{\text{NS}} \) and \( R_{\text{NS}} \)), the effective temperature in the neutron star frame (i.e., non-redshifted; \( kT_{\text{eff}} \)), the source distance (\( D \)) and a normalization factor, which parametrizes the fraction of the surface that is radiating. We keep the latter fixed at 1 throughout this work, which corresponds to the entire neutron star surface emitting. The effective temperature as seen by an observer at infinity is given by \( kT_{\text{eff}}^{\infty} = kT_{\text{eff}} / (1 + z) \), where \( 1 + z = (1 - R_s / R_{\text{NS}})^{-1/2} \) is the gravitational redshift factor, with \( R_s = 2GM_{\text{NS}} / c^2 \) being the Schwarzschild radius, \( G \) the gravitational constant and \( c \) the speed of light.

The XMM-Newton data is well-fitted by an absorbed nsatmos model (\( \chi^2_v = 1.1 \) for
3.2 Observations and data analysis

466 d.o.f.), although significant residuals above the model fit are present for energies \( \gtrsim 2 - 3 \) keV. We model this non-thermal emission by adding a powerlaw component, which significantly improves the fit \( (\chi^2_r = 1.0 \text{ for } 464 \text{ d.o.f.}; \text{ an F-test suggests a } \sim 1 \times 10^{-14} \text{ probability of achieving this level of improvement by chance}) \). Chandra observations carried out in 2008 mid-October, three weeks prior to this XMM-Newton observation, also indicated the presence of a non-thermal component in the quiescent spectrum of EXO 0748–676 (Degenaar et al. 2009). Whereas the Chandra data could not constrain the powerlaw index, the larger collective area of XMM-Newton provides better constraints for the fluxes under consideration.

By using a combined nsatmos and powerlaw model to fit the XMM-Newton data, we obtain a powerlaw index of \( \Gamma = 1.7 \pm 0.5 \), i.e., in between the values of \( \Gamma = 1 \) and \( \Gamma = 2 \) considered by Degenaar et al. (2009). This fit furthermore yields \( N_H = (7 \pm 2) \times 10^{20} \text{ cm}^{-2} \) and \( R_{NS} = 17.8 \pm 1 \text{ km} \), when fixing the neutron star mass to a canonical value of \( M_{NS} = 1.4 \text{ M}_\odot \) and the distance to \( D = 7.4 \text{ kpc} \) (the best estimate from type-I X-ray burst analysis; Galloway et al. 2008a). The resulting powerlaw component contributes \( \sim 10\% \) to the total unabsorbed 0.5–10 keV flux. This is lower than the \( \sim 15 – 20\% \) inferred from the Chandra observations performed in 2008 mid-October (Degenaar et al. 2009). The obtained hydrogen column density is consistent with values found for EXO 0748–676 during its outburst \( (N_H \sim 7 \times 10^{20} – 1.2 \times 10^{21} \text{ cm}^{-2}; \text{ e.g., Sidoli et al. 2005}) \).

The Chandra observations obtained in 2009 February and June are well-fitted by an absorbed nsatmos model and do not require an additional powerlaw component. However, the 2010 April data shows evidence for such a hard tail, as significant residuals are present above the nsatmos model fit for energies \( \gtrsim 2 - 3 \) keV. If we include a powerlaw with photon index \( \Gamma = 1.7 \), as was found from fitting the XMM-Newton data (see above), this model component contributes \( \sim 10, \sim 5 \) and \( \sim 15\% \) to the total unabsorbed 0.5–10 keV flux for the data taken in 2009 February, June and 2010 April, respectively. Figure 3.3 compares the Chandra spectral data obtained on 2008 October and 2010 April, showing that both spectral components decreased over the 18-month time span that separates the two observations. We found no spectral differences between the two separate exposures performed in 2009 February and therefore we tied all spectral parameters between these two spectra in the fits.

The Swift data do not provide sufficient statistics to constrain the presence of a hard spectral component. We include a powerlaw in the fits, but fix both the index and the normalization of this component (see Section 3.3.1). Since it is unclear how the powerlaw exactly evolves over time, we adjust the normalization for the Swift observations such that it always contributes 10\% of the total unabsorbed 0.5–10 keV flux. We first treated each Swift observation separately, but found that the thermal flux and neutron star temperature did not evolve significantly between consecutive
observations. To improve the statistics, we therefore sum the Swift data into groups spanning ~ 1 – 4 weeks of observations, resulting in exposure times of ~ 10 – 20 ks (see Table 3.2). These spectra were grouped to contain at least 20 photons per bin.

3.3 Results

3.3.1 Spectral fits

As discussed in Section 3.2.4, the quiescent spectrum of EXO 0748–676 can be described by a combination of a neutron star atmosphere model and a non-thermal powerlaw tail. We fitted the Chandra and XMM-Newton data simultaneously within Xspec to a combined nspect and powerlaw model subject to interstellar absorption, to explore the best-fit values for the neutron star mass and radius, source distance and hydrogen column density. We include the first set of Chandra observations obtained in 2008 October (discussed in Degenaar et al. 2009) in the analysis. As before, we use the photo model with the default Xspec abundances and cross-sections to take into account the neutral hydrogen absorption along the line of sight. The powerlaw index is fixed to $\Gamma = 1.7$ (the best fit-value obtained from XMM-Newton observations; see Section 3.2.4), because there are not sufficient counts at higher energies in the Chandra spectra to allow this component to vary. The powerlaw normalization is left as a free parameter.

If the neutron star mass and radius are fixed to canonical values of $M_{\text{NS}} = 1.4 \, M_{\odot}$ and $R_{\text{NS}} = 10$ km, and in addition the source distance is fixed to $D = 7.4$ kpc, the hydrogen column density pegs at its lower limit ($N_H = 0$). When the distance is left to vary freely, the best-fit value is $4.6 \pm 0.3$ kpc, which is just outside the range obtained from X-ray burst analysis (5–8.3 kpc; Galloway et al. 2008a). Therefore, we choose to keep the distance fixed at 7.4 kpc, and instead allow the neutron star radius to vary. This way, we obtain best-fit values of $N_H = (7 \pm 1) \times 10^{20}$ cm$^{-2}$ and $R = 15.6 \pm 0.8$ km. If additionally the neutron star mass is left free to vary in the fit, this parameter is not strongly constrained ($M_{\text{NS}} \sim 1.6 \pm 0.6 \, M_{\odot}$). In the final fits we choose to fix the neutron star mass to $M_{\text{NS}} = 1.4 \, M_{\odot}$, because otherwise the uncertainty in this quantity will dominate the errors of the other parameters.

For the final spectral analysis, we fit all XMM-Newton, Chandra and Swift data with an absorbed nstmos plus powerlaw model, where $N_H = 7 \times 10^{20}$ cm$^{-2}$, $M_{\text{NS}} = 1.4 \, M_{\odot}$, $R_{\text{NS}} = 15.6$ km, $D = 7.4$ kpc and $\Gamma = 1.7$ are fixed, while the neutron star effective temperature is left as a free parameter. The powerlaw normalization is left to vary freely for the Chandra and XMM-Newton observations, but fixed for the Swift data (so that this component contributes 10% to the total unabsorbed 0.5–10 keV flux). We fit all data in the 0.5–10 keV energy range and deduce the absorbed
### 3.3 Results

**Table 3.2:** Results from fitting the spectral data.

<table>
<thead>
<tr>
<th>Satellite</th>
<th>Date</th>
<th>∆t (days)</th>
<th>Pow. frac. (%)</th>
<th>$kT_{\text{eff}}^\text{m}$ (eV)</th>
<th>$F_X$</th>
<th>$F_{\text{bol}}^\text{th}$</th>
<th>$L_{\text{bol}}$</th>
<th>$\chi^2$ (d.o.f.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Swift †</td>
<td>2008-09-28 – 2008-10-07</td>
<td>4.9</td>
<td>10 fix</td>
<td>123.7 ± 5.4</td>
<td>1.31 ± 0.22</td>
<td>1.53 ± 0.26</td>
<td>10.0 ± 1.7</td>
<td>0.93 (8)</td>
</tr>
<tr>
<td>Chandra †</td>
<td>2008-10-12/13/15</td>
<td>1.4</td>
<td>20 ± 3</td>
<td>118.8 ± 0.9</td>
<td>1.23 ± 0.02</td>
<td>1.31 ± 0.04</td>
<td>8.6 ± 0.3</td>
<td>1.03 (175)</td>
</tr>
<tr>
<td>Swift †</td>
<td>2008-10-29 – 2008-11-02</td>
<td>2.2</td>
<td>10 fix</td>
<td>118.3 ± 2.6</td>
<td>1.10 ± 0.09</td>
<td>1.28 ± 0.11</td>
<td>8.4 ± 0.7</td>
<td>0.67 (14)</td>
</tr>
<tr>
<td>XMM</td>
<td>2008-11-06</td>
<td>0.2</td>
<td>7 ± 2</td>
<td>120.7 ± 0.4</td>
<td>1.14 ± 0.01</td>
<td>1.39 ± 0.02</td>
<td>9.1 ± 0.1</td>
<td>1.08 (467)</td>
</tr>
<tr>
<td>Swift †</td>
<td>2008-11-28 – 2008-12-20</td>
<td>11.0</td>
<td>10 fix</td>
<td>118.7 ± 2.6</td>
<td>1.11 ± 0.10</td>
<td>1.30 ± 0.12</td>
<td>8.5 ± 0.8</td>
<td>1.09 (14)</td>
</tr>
<tr>
<td>Swift †</td>
<td>2009-01-10 – 2009-01-30</td>
<td>9.8</td>
<td>10 fix</td>
<td>116.2 ± 2.2</td>
<td>0.99 ± 0.07</td>
<td>1.19 ± 0.09</td>
<td>7.8 ± 0.6</td>
<td>1.09 (18)</td>
</tr>
<tr>
<td>Swift</td>
<td>2009-02-13 – 2009-02-23</td>
<td>5.1</td>
<td>10 fix</td>
<td>117.2 ± 2.4</td>
<td>1.02 ± 0.08</td>
<td>1.23 ± 0.10</td>
<td>8.1 ± 0.7</td>
<td>0.50 (15)</td>
</tr>
<tr>
<td>Chandra</td>
<td>2009-02-23/25</td>
<td>0.9</td>
<td>12 ± 4</td>
<td>113.5 ± 1.3</td>
<td>0.91 ± 0.03</td>
<td>1.09 ± 0.05</td>
<td>7.1 ± 0.3</td>
<td>0.90 (139)</td>
</tr>
<tr>
<td>Swift</td>
<td>2009-03-01 – 2009-03-16</td>
<td>7.2</td>
<td>10 fix</td>
<td>115.6 ± 2.3</td>
<td>0.97 ± 0.08</td>
<td>1.17 ± 0.09</td>
<td>7.7 ± 0.6</td>
<td>0.79 (16)</td>
</tr>
<tr>
<td>Swift</td>
<td>2009-04-09 – 2009-04-23</td>
<td>7.1</td>
<td>10 fix</td>
<td>112.2 ± 2.8</td>
<td>0.86 ± 0.09</td>
<td>1.03 ± 0.11</td>
<td>6.8 ± 0.7</td>
<td>1.16 (10)</td>
</tr>
<tr>
<td>Swift</td>
<td>2009-05-07 – 2009-06-05</td>
<td>14.7</td>
<td>10 fix</td>
<td>114.2 ± 2.3</td>
<td>0.92 ± 0.07</td>
<td>1.11 ± 0.09</td>
<td>7.3 ± 0.6</td>
<td>0.88 (16)</td>
</tr>
<tr>
<td>Chandra</td>
<td>2009-06-10</td>
<td>0.2</td>
<td>4 ± 3</td>
<td>111.0 ± 0.7</td>
<td>0.75 ± 0.01</td>
<td>0.99 ± 0.03</td>
<td>6.5 ± 0.2</td>
<td>1.19 (93)</td>
</tr>
<tr>
<td>Swift</td>
<td>2009-06-11 – 2009-07-03</td>
<td>11.5</td>
<td>10 fix</td>
<td>111.9 ± 2.2</td>
<td>0.75 ± 0.07</td>
<td>1.03 ± 0.08</td>
<td>6.7 ± 0.5</td>
<td>0.99 (17)</td>
</tr>
<tr>
<td>Swift</td>
<td>2009-07-18 – 2009-07-31</td>
<td>6.9</td>
<td>10 fix</td>
<td>110.5 ± 2.1</td>
<td>0.79 ± 0.06</td>
<td>0.98 ± 0.07</td>
<td>6.4 ± 0.5</td>
<td>0.42 (18)</td>
</tr>
</tbody>
</table>

Note. – Observations marked by a dagger were already discussed in Degenaar et al. (2009), but refitted in this work. Quoted errors represent 90% confidence levels. $F_X$ represents the 0.5–10 keV total model flux and $F_{\text{bol}}^\text{th}$ gives the 0.01–100 keV x-rays flux (both unabsorbed and in units of $10^{-12}$ erg cm$^{-2}$ s$^{-1}$). $L_{\text{bol}}$ gives the 0.01–100 keV luminosity of the x-rays component in units of $10^{33}$ erg s$^{-1}$ and assuming $D = 7.4$ kpc. ∆t represents the time interval of the observations and the fractional powerlaw contribution is given in a percentage of the total unabsorbed 0.5–10 keV flux.
Table 3.2: Continued.

<table>
<thead>
<tr>
<th>Satellite</th>
<th>Date</th>
<th>∆t (days)</th>
<th>Pow. frac. (%)</th>
<th>kT_∞ (eV)</th>
<th>F_X</th>
<th>F^th_p</th>
<th>L_bol</th>
<th>χ^2 (d.o.f.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Swift</td>
<td>2009-08-15 – 2009-09-09</td>
<td>12.7</td>
<td>10 fix</td>
<td>110.0 ± 1.8</td>
<td>0.78 ± 0.05</td>
<td>0.96 ± 0.06</td>
<td>6.3 ± 0.4</td>
<td>1.30 (26)</td>
</tr>
<tr>
<td>Swift</td>
<td>2009-10-01 – 2009-11-05</td>
<td>17.4</td>
<td>10 fix</td>
<td>108.0 ± 2.6</td>
<td>0.69 ± 0.07</td>
<td>0.88 ± 0.09</td>
<td>5.8 ± 0.6</td>
<td>1.49 (11)</td>
</tr>
<tr>
<td>Swift</td>
<td>2009-12-21 – 2010-10-01</td>
<td>10.2</td>
<td>10 fix</td>
<td>109.4 ± 2.0</td>
<td>0.74 ± 0.06</td>
<td>0.94 ± 0.07</td>
<td>6.1 ± 0.5</td>
<td>1.51 (19)</td>
</tr>
<tr>
<td>Swift</td>
<td>2010-02-12 – 2010-03-13</td>
<td>15.0</td>
<td>10 fix</td>
<td>109.4 ± 2.0</td>
<td>0.76 ± 0.06</td>
<td>0.94 ± 0.07</td>
<td>6.1 ± 0.5</td>
<td>1.25 (20)</td>
</tr>
<tr>
<td>Chandra</td>
<td>2010-04-20</td>
<td>0.2</td>
<td>15 ± 4</td>
<td>108.6 ± 1.1</td>
<td>0.77 ± 0.02</td>
<td>0.91 ± 0.04</td>
<td>6.0 ± 0.2</td>
<td>0.79 (91)</td>
</tr>
</tbody>
</table>

and unabsorbed fluxes in this band. The thermal model fit is extrapolated to the energy range of 0.01–100 keV to estimate the thermal bolometric flux. The results from fitting the X-ray spectra in this way are presented in Table 3.2. The effective temperatures and thermal bolometric fluxes derived from Chandra, Swift and XMM-Newton data are displayed in Figure 3.4. Examination of Figure 3.4 suggests that there is a small but discernible offset in the thermal flux and neutron star temperature as deduced from the different satellites. This is briefly discussed in Section 3.3.3.

3.3.2 Lightcurve fits

Figure 3.4 clearly reveals a decaying trend in thermal flux and temperature. To investigate the decay shape, we fit the temperature curve with an exponential decay function of the form \( y(t) = a e^{-(t-t_0)/\tau} \), where \( a \) is a normalization constant, \( t_0 \) is the start time of the cooling curve and \( \tau \) the e-folding time. Given the apparent offset between the different instruments (see Section 3.3.3), we perform different fits to the Chandra and Swift data. We fix \( t_0 \) to 2009 September 5 (MJD 54714), which is in between the first non-detection by RXTE/PCA and the first Swift/XRT observation of the source (Degenaar et al. 2009).

The simple exponential decay, represented by the dotted lines in Figure 3.5, yields an e-folding time of \( 6121.7 \pm 2004.0 \) days for the Chandra data, but does not provide a good fit (\( \chi^2 = 6.0 \) for 2 d.o.f.). For the Swift lightcurve we find \( \tau = 5328.1 \pm 674.7 \) days (\( \chi^2 = 0.5 \) for 12 d.o.f.). If we include a constant offset (i.e., \( y(t) = a e^{-(t-t_0)/\tau} + b \); solid lines in Figure 3.5), we obtain a better fit for the Chandra data, yielding a normalization of \( a = 13.4 \pm 0.2 \) eV, an e-folding decay time of
Figure 3.4: Evolution of the bolometric flux (top) and effective temperature (bottom) of EXO 0748–676, deduced from Chandra/ACIS-S (black squares), Swift/XRT (grey triangles) and XMM-Newton/EPIC (black star) data. Multiple Swift observations were summed to improve the data statistics.

$\tau = 191.6 \pm 9.7$ days and a constant offset of $b = 107.9 \pm 0.2$ eV ($\chi^2_\nu = 0.02$ for 1 d.o.f.). For the Swift data we find $a = 17.2 \pm 1.8$ eV, $\tau = 265.6 \pm 100.0$ days and $b = 106.2 \pm 2.5$ eV ($\chi^2_\nu = 0.34$ for 11 d.o.f.), consistent with the Chandra fit.

Although an exponential decay provides an adequate description of the data of EXO 0748–676, as has been found for other sources (e.g., Cackett et al. 2006; Fridriksson et al. 2010), mathematically a neutron star crust is expected to cool via a (broken) powerlaw (Eichler & Cheng 1989; Brown & Cumming 2009). If we fit a single powerlaw of the form $y(t) = A(t - t_0)^B$ to the Chandra data, we find an index of $B = -0.03 \pm 0.01$ and a normalization of $A = 134.4 \pm 1.0$ eV ($\chi^2_\nu = 0.13$ for 2 d.o.f.). For the Swift observations we find $B = -0.05 \pm 0.01$ and $A = 144.7 \pm 3.8$ eV ($\chi^2_\nu = 0.4$ for 12 d.o.f.). These powerlaw fits are indicated by the dashed lines in Figure 3.5.

A broken powerlaw also yields an acceptable fit to the Swift data ($\chi^2_\nu = 0.3$ for 10 d.o.f.). We find a normalization of $A = 135.0 \pm 17.8$ eV, a break at $166.0 \pm 99.2$ days and decay indices of $-0.03 \pm 0.03$ and $-0.06 \pm 0.02$ before and after the break, respectively. This fit is indicated by the dashed-dotted curve in Figure 3.5. There are not sufficient Chandra observations to fit a broken powerlaw decay. We note that the shape of the decay curve of EXO 0748–676 is not strongly affected by
Figure 3.5: Evolution of the effective temperature of EXO 0748–676 fitted to different decay functions (see Section 3.3.2). The left image displays Chandra data and exponential decay fits both with and without a constant offset (solid and dotted line, respectively), as well as a decaying powerlaw (dashed curve). The right image shows Swift observations, where the dashed line is again a powerlaw fit, while the solid and dotted curves are exponential decays. In addition, this plot includes a fit to a broken powerlaw, which is represented by the dashed-dotted line.

our choice of spectral parameters ($N_H$, $M_{NS}$, $R_{NS}$, and $\Gamma$) or assumed distance (see also previous studies by e.g., Wijnands et al. 2004; Cackett et al. 2008a).

3.3.3 Instrument cross-calibration

The quiescent lightcurve presented in Figure 3.4 shows indications that the thermal flux and temperature inferred from the Chandra observations lie below the trend of the Swift data points. This possible shift (~ 6% for the flux lightcurve) may be due to cross-calibration issues between the two satellites. A study of the Crab nebula indeed revealed an offset between Chandra and Swift, whereas such a discrepancy was not found between Swift and XMM-Newton (Kirsch et al. 2005). This might be reflected in our results as well, since the XMM-Newton data point appears to line up with the trend indicated by the Swift data. However, our Chandra and Swift data points may also be (partly) offset due to the fact that we cannot constrain the powerlaw component in the Swift data, which we therefore fixed to contribute 10% of the total 0.5–10 keV unabsorbed flux (see Section 3.2.4).
3.4 Discussion

We discuss *Chandra*, *Swift* and *XMM-Newton* observations obtained after the cessation of the very long (∼24 year) active period of EXO 0748–676. Fitting the spectral data with a neutron star atmosphere model *nsatmos*, did not reveal clear indications of a changing thermal spectrum during the first five months of the quiescent phase (Degenaar et al. 2009). However, now that the quiescent monitoring has extended to 19 months (1.6 years), we find a significant decrease in neutron star effective temperature from $kT_{\text{eff}}^{\infty} \sim 124$ to 109 eV. The thermal bolometric flux was observed to decay from $F_{\text{th bol}}^{\text{th}} \sim 1.5 \times 10^{-12}$ to $0.9 \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$.

In addition to a soft, thermal component, the *Chandra* and *XMM-Newton* observations show evidence for a hard powerlaw tail with index $\Gamma = 1.7$. The fractional contribution of the hard spectral component to the total unabsorbed 0.5–10 keV flux initially decreased from $\sim 20\%$ in 2008 October to $\sim 4\%$ in 2009 June. However, observations carried out in 2010 April suggest that the powerlaw fraction increased again to $\sim 15\%$. Similar behaviour has been observed for several other quiescent neutron star systems (Jonker et al. 2004; Jonker 2008), although others show more irregular behaviour (Fridriksson et al. 2010). In Cen X-4, the powerlaw tail in the quiescent spectrum shows variations that appear to be linked to changes in the thermal component, possibly caused by low-level accretion (Cackett et al. 2010b).

The gradual decrease in thermal flux and neutron star temperature observed for EXO 0748–676 can be interpreted as the neutron star crust cooling down in quiescence after it has been heated during its long accretion outburst. Figure 3.6 compares our data of EXO 0748–676 with the crust cooling curves observed for the neutron star X-ray binaries KS 1731–260, MXB 1659–29 and XTE J1701–462. This plot shows that the amount of cooling following the end of the outburst is markedly smaller for EXO 0748–676 than for the other three sources. We have observed our target over the first 19 months after the cessation of the outburst and during this time the thermal bolometric flux has decreased by a factor of $\sim 1.7$. In a similar time span, the thermal bolometric fluxes of KS 1731–260, MXB 1659–29 and XTE J1701–462 had decreased by a factor of $\sim 3.5$, 6 and 2.5, respectively (see Cackett et al. 2006; Fridriksson et al. 2010). The effective neutron star temperature of EXO 0748–676 has decreased by about 10%, compared to $\sim 30$, 40 and 20% for KS 1731–260, MXB 1659–29 and XTE J1701–462.

Although the observed fractional changes in neutron star temperature and thermal bolometric flux are smaller for EXO 0748–676 than for the other three sources, the decay itself may not be markedly different. The quiescent lightcurves of KS 1731–260, MXB 1659–29 and XTE J1701–462 can be fit with an exponential decay function levelling off to a constant value, yielding e-folding times of $\sim 305 \pm 50$, $\sim 465 \pm 25$ and $\sim 120 \pm 25$ days, respectively (Cackett et al. 2008a; Fridriksson
For the Chandra data of EXO 0748–676, we find an e-folding time of \( \sim 192 \pm 10 \) days (see Section 3.3.2). These decay times provide a measure of the thermal relaxation time of the neutron star crust, which depends on the composition and structure of the lattice, the distribution of heating sources and the thickness of the crust (e.g., Lattimer et al. 1994; Rutledge et al. 2002b; Shternin et al. 2007; Brown & Cumming 2009).

Rutledge et al. (2002b) and Shternin et al. (2007) calculate theoretical cooling curves for KS 1731–260, assuming different physics for the crust and core. These authors present simulations for both an amorphous crust and an ordered crystalline lattice. For the latter, the spread of nuclide charge numbers \((Z)\) in the crust matter is small, which is referred to as a low level of impurities and results in a highly conductive crust. A large number of impurities gives an amorphous structure, which affects the thermal properties of the crust and results in a low conductivity. In addition, Rutledge et al. (2002b) explore standard (i.e., slow) and enhanced neutrino cooling mechanisms, yielding different core temperatures. Comparing our results on EXO 0748–676 with the decay shapes resulting from those calculations suggests that the neutron star has a highly conductive crust, similar to what has been inferred for the other three sources (Wijnands et al. 2002a, 2004; Cackett et al. 2006; Shternin et al. 2007; Brown & Cumming 2009; Fridriksson et al. 2010). The fact that the decay curve of EXO 0748–676 is rather shallow may be explained in terms of a relatively small temperature gradient and thus lower thermal flux across the core-crust boundary (cf. the model curves for a highly conductive crust and different core temperatures presented by Rutledge et al. 2002b). This can be due to a combination of a warm neutron star core and a relatively low mass-accretion rate during outburst.

Comparing the exponential decay fit to the Chandra data of EXO 0748–676 indicates that the neutron star crust might already be close to restoring equilibrium with the core. The fit results in a quiescent base level of \(107.9 \pm 0.2\) eV, while we found a temperature of \(108.6 \pm 1.1\) eV for the observation performed in 2010 April. Prior to its last outburst, EXO 0748–676 was observed in quiescence with the Einstein observatory, displaying a \(0.5–10\) keV unabsorbed flux of \(8.4^{+4.2}_{-1.7} \times 10^{-13}\) erg cm\(^{-2}\) s\(^{-1}\) (Garcia & Callanan 1999). Our Chandra observations of 2010 April detected EXO 0748–676 at a \(0.5–10\) keV unabsorbed flux of \((7.7 \pm 0.2) \times 10^{-13}\) erg cm\(^{-2}\) s\(^{-1}\) (see Table 3.2). Assuming that the Einstein detection caught EXO 0748–676 at its quiescent base level, this supports the idea that the crust has nearly cooled down. This would imply that the neutron star core in EXO 0748–676 is relatively hot (cf. Heinke et al. 2009b), suggesting that either standard cooling mechanisms are operating and that the neutron star is not very massive, or that the time-averaged mass-accretion rate of the system is very high due to a short recurrence time (see below).

The energy deposited during outburst is \(L_{\text{nuc}} \sim \langle M \rangle Q_{\text{nuc}} / m_u\) (e.g., Brown et al. 2009b).
1998; Colpi et al. 2001). Here, \(Q_{\text{nuc}} \sim 2\) MeV is the nuclear energy deposited per accreted baryon (Gupta et al. 2007; Haensel & Zdunik 2008), \(m_0\) is the atomic mass unit and \(\langle \dot{M} \rangle\) is the time-averaged accretion rate of the system. The latter can be expressed as \(\langle \dot{M} \rangle = \langle \dot{M}_{\text{ob}} \rangle \times t_{\text{ob}} / t_{\text{rec}}\), where \(\langle \dot{M}_{\text{ob}} \rangle\) is the average accretion rate during outburst episodes, \(t_{\text{ob}}\) is the outburst duration and \(t_{\text{rec}}\) is the system’s recurrence time.

The factor \(t_{\text{ob}} / t_{\text{rec}}\) represents the duty cycle of the system. The neutron star core is expected to be in a steady state, in which the energy radiated during quiescence balances the heat deposited during outburst. We can thus obtain an estimate of the duty cycle of EXO 0748–676 by equating the heating and cooling rates.

A neutron star cools primarily via photon radiation from the surface and neutrino emissions from the stellar core. If the lightcurve of EXO 0748–676 has indeed (nearly) levelled off, the bolometric luminosity emitted as photons is thus \(L_\gamma \sim 6 \times 10^{33} (D/7.4\) kpc\(^2\) \) erg s\(^{-1}\) (as measured during the Chandra observation of 2010 April). The rate of neutrino emissions depends on the temperature of the neutron star core, which can be estimated from the effective surface temperature once the crust has thermally relaxed. A quiescent base level of \(kT_{\text{eff}} \sim 108\) eV (as suggested by exponential decay fits to the Chandra data), implies an effective surface temperature in the neutron star frame of \(kT_{\text{eff}} \sim 1.3 \times 10^8\) K. For such a core temperature, the minimum energy escaping the neutron star as neutrino’s (i.e., assuming standard core cooling) is \(L_\nu \sim 10^{34-35}\) erg s\(^{-1}\) (Page et al. 2006).

Equating the energy losses via photon radiation from the neutron star surface (\(L_\gamma\)) and neutrino emissions from the stellar core (\(L_\nu\)) with the energy gained via crustal reactions during outburst (\(L_{\text{nuc}}\)), suggests that EXO 0748–676 must have a time-averaged mass-accretion rate of \(\langle \dot{M} \rangle \gtrsim 8 \times 10^{15}\) g s\(^{-1}\). During outburst, EXO 0748–676 displayed an average bolometric luminosity of \(\sim 6 \times 10^{36} (D/7.4\) kpc\(^2\) \) erg s\(^{-1}\) (Sidoli et al. 2005; Boirin et al. 2007). For an accretion luminosity is given by \(L_{\text{acc}} = (GM_{\text{NS}} / R_{\text{NS}})\langle \dot{M}_{\text{ob}} \rangle\), this translates into a mass-accretion rate of \(\langle \dot{M}_{\text{ob}} \rangle \sim 3 \times 10^{16}\) g s\(^{-1}\) for a canonical neutron star with \(M = 1.4\) M\(_{\odot}\) and \(R = 10\) km.\(^3\)

If the crust has indeed thermally relaxed, the above estimates show that EXO 0748–676 must have a duty cycle of \(\gtrsim 30\%\) to explain the observed quiescent bolometric luminosity of \(\sim 6 \times 10^{33} (D/7.4\) kpc\(^2\) \) erg s\(^{-1}\) in terms of thermal emission from the cooling neutron star (i.e., opposed to continued accretion). The outburst of EXO 0748–676 started between 1980 May and 1984 July and the system returned

\(^3\)We note that EXO 0748–676 is an eclipsing system and therefore part of the central X-ray flux may be intercepted from our line of sight. However, the X-ray burst behaviour of the source is consistent with the mass-accretion rate inferred from the observed X-ray luminosity (Boirin et al. 2007).
to quiescence in 2008 September, i.e., $t_{ob} = 24 - 28$ years. If the observed outburst is typical for the long-term behaviour of this source, the expected recurrence time is thus $\lesssim 100$ years. In case the neutron star cools via more efficient core neutrino emission processes, the recurrence time required to explain the observed quiescent luminosity is shorter (i.e., the duty cycle is higher). Although the above calculation is only a crude approximation (e.g., there is a significant uncertainty in the relation between the surface- and interior temperature of the neutron star, depending on the atmospheric composition and the depth of the light element layer; Brown & Cumming 2009), it illustrates that EXO 0748–676 must have a high duty cycle if the cooling curve has indeed reached its quiescent base level.

Brown et al. (1998), Rutledge et al. (2000) and Colpi et al. (2001) have suggested that EXO 0748–676 continues to accrete in quiescence, because the quiescent luminosity inferred from the 1980 Einstein observation is higher than predicted by standard cooling models. However, these conclusions are based on an assumed duty cycle of $\sim 1\%$, but we have no a priori knowledge about this. Although we cannot exclude that the system is indeed accreting in quiescence, the above estimates show that a duty cycle of $\gtrsim 30\%$ can explain the observed quiescent level of EXO 0748–676 as being due to thermal emission from the cooling neutron star. A duty cycle of $\gtrsim 30\%$ is high, although not unprecedented for neutron star transients (e.g., Chen et al. 1997; Degenaar & Wijnands 2009).

Recently, Brown & Cumming (2009) demonstrated that the cooling of a neutron star crust is expected to follow a broken powerlaw decay. A break is predicted to occur due to a transition in the crystal structure of the crust matter, and the slope before the break reflects the heat flux from the outer crustal layers. Therefore, we also fitted the neutron star temperatures obtained for EXO 0748–676 to a powerlaw and found decay indices of $-0.03 \pm 0.01$ and $-0.05 \pm 0.01$ for the Chandra and Swift data sets, respectively. The Swift observations indicate that a possible break in the quiescent lightcurve may have occurred $\sim 67 - 265$ days after the cessation of the outburst (see Section 3.3.2). By fitting a broken powerlaw function, we obtain a decay index of $-0.03 \pm 0.03$ before the break, which steepens to $-0.06 \pm 0.02$ thereafter. However, since these slopes are consistent with being equal, further observations are required to confirm whether a break has indeed occurred.

The decay parameters that we find for EXO 0748–676 are comparable to that obtained by Fridriksson et al. (2010) for XTE J1701–462. These authors found that the quiescent lightcurve breaks $\sim 20 - 150$ days post-outburst and report decay indices of $-0.03$ and $-0.07$ before and after the break, respectively. Fridriksson et al. (2010) note that possible cross-calibration effects between Chandra and XMM-Newton might introduce small shifts that also allow a single powerlaw decay with slope $-0.05$. The cooling curves of KS 1731–260 and MXB 1659–29 appear to
3.4 Discussion

have steeper decays with indices of $\sim -0.12$ and $\sim -0.33$, respectively (Cackett et al. 2008a). Due to the scarcity of data points it is unclear whether a break occurred in the quiescent lightcurves of the latter two sources (Cackett et al. 2008a; Brown & Cumming 2009).

The powerlaw fits show no indications that the quiescent lightcurve of EXO 0748–676 is levelling off. Thus, it is also possible that the neutron star temperature continues to decay further and that the core is cooler than suggested by the exponential decay fits and the 1980 Einstein detection. The relatively slow decrease of EXO 0748–676 might then reflect that the crust has a high conductivity, albeit lower than that of the neutron stars in KS 1731–260 and MXB 1659–29. Further observations are thus required to determine whether the neutron star crust in EXO 0748–676 has nearly cooled down and to be able to draw firm conclusions on the crust and core properties.

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Figure 3.6: The effective temperatures of KS 1731–260 (green diamonds; from Cackett et al. 2006), MXB 1659–29 (red bullets; from Cackett et al. 2006, 2008a), XTE J1701–462 (grey crosses; from Fridriksson et al. 2010) and EXO 0748–676 (black squares, triangles and star). Exponential decay fits to the data of KS 1731–260, MXB 1659–29 and XTE J1701–462 are shown to guide the eye (green dashed, red dashed-dotted and grey dotted line, respectively). The two data points of XTE J1701–462 that lie above the decay fit are likely due to a temporary increase in the accretion rate causing reheating of the neutron star (Fridriksson et al. 2010).
Multi-wavelength observations of 1RXH J173523.7–354013: revealing an unusual bursting neutron star


Abstract – On 2008 May 14, the Burst Alert Telescope onboard the Swift mission triggered on a type-I X-ray burst from the previously unclassified ROSAT object 1RXH J173523.7–354013, establishing the source as a neutron star X-ray binary. We report on X-ray, optical and near-infrared observations of this system. The X-ray burst had a duration of ~ 2 h and belongs to the class of rare, intermediately long type-I X-ray bursts. From the bolometric peak flux of \( \sim 3.5 \times 10^{-8} \) erg cm\(^{-2}\) s\(^{-1}\), we infer a source distance of \( D \approx 9.5 \) kpc. Photometry of the field reveals an optical counterpart that declined from \( R = 15.9 \) during the X-ray burst to \( R = 18.9 \) thereafter. Analysis of post-burst Swift/XRT observations, as well as archival XMM-Newton and ROSAT data suggests that the system is persistent at a 0.5–10 keV luminosity of \( \sim 2 \times 10^{35} (D/9.5 \text{ kpc})^2 \) erg s\(^{-1}\). Optical and infrared photometry together with the detection of a narrow H\(\alpha\) emission line (FWHM = 292 ± 9 km s\(^{-1}\), EW = −9.0 ± 0.4 Å) in the optical spectrum confirms that 1RXH J173523.7–354013 is a neutron star low-mass X-ray binary. The H\(\alpha\) emission demonstrates that the donor star is hydrogen-rich, which effectively rules out that this system is an ultra-compact X-ray binary.
Multi-wavelength observations of 1RXJ173523.7−354013

4.1 Introduction

The brightest Galactic X-ray point sources are X-ray binaries, in which either a neutron star or a black hole accretes mass from a companion star. When the accretion flow is continuous and the X-ray luminosity remains constant within a factor of a few, a system is classified as persistent. Transient X-ray binaries, on the other hand, alternate accretion outbursts that typically last for weeks to months with years to decades long episodes of quiescence, during which the X-ray luminosity is more than 2 orders of magnitude lower.

One of the phenomena that uniquely mark the compact primary as a neutron star are type-I X-ray bursts (or shortly 'X-ray bursts'); bright flashes of X-ray emission that are caused by unstable nuclear burning on the surface of the neutron star. They are characterised by blackbody emission with a peak temperature $kT_{bb} > 2$ keV and generally display a fast rise time followed by a slower decay phase. The initial rise can be interpreted as burning of the fuel layer, while the subsequent decay represents the cooling of the ashes. So far, X-ray bursts have only been detected from low-mass X-ray binaries (LMXBs), in which the donor star has a mass $M \lesssim 1 M_\odot$. The properties (e.g., duration, radiated energy and recurrence time) of type-I X-ray bursts depend on the conditions of the ignition layer, such as the temperature, thickness and hydrogen (H) abundance. These can drastically change as the mass-accretion rate onto the neutron star varies, which results in X-ray bursts with different characteristics for different accretion regimes (for reviews, see e.g., Lewin et al. 1995; Strohmayer & Bildsten 2006).

X-ray bursts can be serendipitously detected by the Burst Alert Telescope (BAT; Barthelmy et al. 2005) onboard the Swift satellite; a multi-wavelength observatory that is dedicated to the study of gamma-ray bursts (GRBs). Although events from known X-ray burst sources are ignored, the BAT occasionally triggers on an X-ray burst from a previously unknown burster (e.g., in’t Zand et al. 2008; Linares et al. 2009b; Wijnands et al. 2009). On 2008 May 14 at 10:32:37 UT, Swift’s BAT registered an X-ray flare (Krimm et al. 2008). The BAT lightcurve and soft X-ray spectrum (no photons detected above $\sim 35$ keV) suggested that this event was not a GRB (Baumgartner et al. 2008; Krimm et al. 2008). Rapid follow-up observations with the X-ray Telescope (XRT; Burrows et al. 2005) detected a bright, but quickly fading X-ray source within the 3$\sigma$ BAT error circle (Krimm et al. 2008; Baumgartner et al. 2008). Simultaneously obtained UV/Optical Telescope (UVOT; Roming et al. 2005) images revealed a fading source within the XRT error circle (Israel et al. 2008).

The UVOT detection allowed for an accurate localisation of the source of the BAT trigger: $\alpha = 17^h35^m23.75^s$, $\delta = -35^\circ40'16.1''$ (J2000) with a 90% confidence radius of 0.56$''$ (Israel et al. 2008). Both the XRT and the UVOT position coincide with that of the unclassified X-ray source 1RXJ173523.7−354013
4.2 Observations and data reduction

(=1RXS J173524.4–353957=RX J1735.3–3540; ‘J1735’ hereafter), which was discovered with the ROSAT satellite in 1990. The BAT trigger was likely the result of an X-ray burst from this system (Israel et al. 2008), and would thereby identify J1735 as a neutron star in, most likely, an LMXB. We note that Rodriguez et al. (2009) used Swift/XRT observations discussed in this paper to obtain a 3.5” position for the likely hard X-ray counterpart of J1735, IGR J17353–3539 (see Section 4.2.5). Based on that position, the authors identify a bright counterpart candidate in 2MASS ($K_s=8.63 \pm 0.03$) and USNO-B1.0 ($V=11.9 \pm 0.3$) catalogues, suggesting a possible high-mass X-ray binary nature. This object is also visible in our optical and near-infrared (near-IR) observations, but although it is very close to J1735 (∼4” NW; see Figure 4.3), it lies well outside the sub-arcsecond UVOT position and is therefore not its counterpart.

In this paper we report on a multi-wavelength observing campaign of J1735 following the BAT trigger of 2008 May 14. We discuss the properties of the X-ray burst and the characteristics of the persistent emission. Our study comprises Swift data obtained with the BAT, XRT and UVOT, optical photometric observations carried out with the Rapid Eye Mount (REM) and the New Technology Telescope (NTT), optical spectroscopy using the Very Large Telescope (VLT), as well as near-IR observations performed with the Magellan Baade telescope. In addition, we explore archival ROSAT, Integral and XMM-Newton data to investigate the long-term flux and X-ray burst behaviour of J1735.

4.2 Observations and data reduction

The observations that we obtained of J1735 with different facilities are listed in Table 4.1. In the following sections these are discussed in more detail.

4.2.1 Swift

BAT

We generated standard BAT data products for the trigger observation using the BATGRBPRODUCT tool. The 15–35 keV BAT lightcurve of the burst, shown in Figure 4.1, is consistent with a single peak centred at $t \sim 0$ s and emerging from the background for $\sim 200$ s, with a very slow rise time of $\sim 100$ s (Baumgartner et al. 2008; Israel et al. 2008).\(^1\) The apparent peak at $t \sim 90$ s is thought to be an artefact related to the spacecraft slewing, whereas the apparent rise in count rate after $t \sim 120$ is likely caused by entering the South Atlantic Anomaly (SAA; Baumgartner et al. 2008).

\(^1\)See also http://gcn.gsfc.nasa.gov/notices_s/311603/BA.
Figure 4.1: Background subtracted lightcurve of J1735 from Swift/BAT data, binned by 10 s (15–35 keV). The times at which the spacecraft started and finished slewing are indicated by the dashed lines.

The spacecraft started slewing $\sim 75$ s after the burst trigger, by which time the BAT count rate had nearly dropped to the background level (see Figure 4.1). Therefore, we used only pre-slew data and extracted a single BAT spectrum of 140 s around the burst peak using the tool BATbinevt. Given the low count rate, it is not useful to divide the BAT data in multiple bins with a higher time resolution. Necessary geometrical corrections were applied with BATUPDTEPHAKW and the BAT-recommended systematical error was administered using BATHASYSERR. We generated a single response matrix by running the task BATRMGEN and fitted the BAT spectrum between 15–35 keV with Xspec (v.12.5; Arnaud 1996).

About 144 s after the BAT trigger, follow-up observations with the narrow-field XRT and UVOT commenced. These observations typically consists of a number of short data segments ($\lesssim$ 2 ks), which represent different satellite orbits.

XRT

The first XRT data set (ID 311603000) was obtained in windowed timing (WT) mode and consisted of two segments, the first of which lasted for 82 s from 2008 May 14 10:35:05-10:36:27 UT. The source displays a rapid fading during this observation. After a data gap of more than one hour the source was observed for another 8 s
Observations and data reduction

Table 4.1: Observation log.

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Obs ID</th>
<th>Date</th>
<th>$t_{exp}$ (ks)</th>
<th>Wave band</th>
</tr>
</thead>
<tbody>
<tr>
<td>Swift/BAT</td>
<td>311603000</td>
<td>2008-05-14</td>
<td>0.5</td>
<td>15–150 keV</td>
</tr>
<tr>
<td>REM/ROSS</td>
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<td>1.5 $\times 10^{-1}$</td>
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<tr>
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<tr>
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</tbody>
</table>

from 11:44:40 to 11:44:48 UT. By this time the source count rate had decreased from ~ 100 counts s$^{-1}$ down to ~ 1 counts s$^{-1}$ (see Figure 4.2), which caused an automatic switch to the photon counting mode (PC). The PC data runs from 2008 May 14 11:44:50 to 12:19:20 UT, amounting to 2068.5 s of exposure time (ID 311603000). A continued fading is apparent in the X-ray lightcurve of this observation, which suggests that the X-ray burst was ongoing.

During subsequent observations performed the next day (ID 311603001; WT mode), the source was detected at a count rate of ~ 0.13 counts s$^{-1}$. In the following months it remained at that level fluctuating by a factor of ~ 2 between ~ 0.06 – 0.18 counts s$^{-1}$ (see Table 4.2). This indicates that the source had returned to its persistent level the day after the BAT trigger. Figure 4.2 displays the lightcurve of all XRT data obtained in 2008. The intensity levels detected with ROSAT in 1990 and 1994 (see Section 4.2.4) are also indicated in this plot.

To obtain clean data products we processed all raw XRT data with the task xrt-pipeline using standard quality cuts and selecting event grades 0–12 for the PC mode.
and 0–2 in the WT mode. Source lightcurves and spectra were extracted with XSELECT (v.2.3). We used a region of \(40 \times 40\) pixels to extract source events from the WT data. A region of similar shape and size, positioned on an empty part well outside the point spread function of the source, was used for the background. For the PC mode observations we used a circular region with a 10 pixel radius to extract source photons. An annulus with an inner (outer) radius of 75 (100) pixels, centred on the source position, served as the background reference. We generated exposure maps with the task XRTEXPOMAP and ancillary response files (arf) were created with XRTPKARF. The response matrix files (v.11; rmf) were obtained from the CALDB database.

The spectra were grouped using the ftools GRPHIA to contain bins with a minimum number of 20 photons. We fitted the spectra with XSPEC in the 0.5–10 keV range. The PC data of observation 311603000 was affected by pile-up. Following the Swift analysis threads, we attempted to correct for the consequent effect on spectral shape and loss in source flux by using an annulus with an inner (outer) radius of 4 (10) pixels as the source extraction region.

We performed time-resolved spectroscopy of the fading tail of the X-ray burst using the XRT observations of May 14 (both WT and PC mode data; ID 311603000). The first set of WT data was divided into 4 intervals of 20 s, each with a total of \(\approx 2000\) counts per interval. We do not include the second set of WT data in the analysis, since this 8 s exposure collected only 14 source photons and the consecutive PC data provide better statistics. The \(\approx 2\) ks PC mode observation consists of a single data segment, which was split into two intervals of similar length, containing \(\approx 500\) counts each after pile-up correction.

We searched the \(\approx 90\) s long WT observation of the X-ray burst for periodicities by means of Fast Fourier Transforms (FFTs) and applying the method described in Israel & Stella (1996). The analysed period range spans from \(\approx 3.5\) ms up to 100 s (\(\approx 262\) 000 total period trials) and the Nyquist frequency is \(\approx 283\) Hz. No significant peaks were found. Meaningful upper limits (\(<100\%\) pulsed fraction) are obtained only for periods shorter than 5 s and range between \(\approx 15\) and \(\approx 20\%\).

To characterise the persistent emission, we used the data obtained from May 15 onwards (IDs 311603001–311603015). The upper left panel of Figure 4.3 displays a summed X-ray image of all PC mode observations of the post-burst epoch. We obtained another Swift/XRT pointing in late July 2009 (ID 31446001) to investigate the state of the system more than a year after the X-ray burst. During that observation, J1735 is detected at a count rate of \(\approx 0.11\) counts s\(^{-1}\). This is the same level as detected in 2008 May–August (see also Table 4.2), which indicates that the system is still actively accreting (see Sections 4.3 and 4.4).

\(^2\)See http://heasarc.gsfc.nasa.gov/docs/swift/analysis for standard Swift analysis threads.
\(^3\)See http://www.swift.ac.uk/pileup.shtml.

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4.2 Observations and data reduction

Figure 4.2: *Swift*/XRT lightcurve of J1735 obtained in 2008. For representation purposes different time bins have been chosen; the first two data sets (respectively WT and PC mode data of observation 311603000) have a time resolution of 10 s, while that of later observations (ID 311603001 onwards) is 1000 s. The two dashed lines represent the intensity levels detected by *ROSAT* in 1990 (PSPC) and in 1994 (HRI) converted to XRT count rates (see Section 4.2.4).

UVOT

The UVOT data of J1735 was obtained using a variety of filters, but the source could only be detected in the broadband white filter (WH, \( \sim 1500 - 8500 \) Å). The upper right panel of Figure 4.3 shows an UVOT WH-band image of the field around J1735 and Table 4.1 gives an overview of the UVOT observations obtained with this filter. Avoiding a nearby object (see Figure 4.3), we used a circular region with a radius of 2″ to extract source photons, and a source-free region with a radius of 10″ as a background reference. Magnitudes were extracted using the tool uvotsource, taking into account aperture corrections.

During the X-ray burst decay, there were three intervals of UVOT observations using the WH-filter. The bottom panel of Figure 4.4 shows the evolution of the magnitude during these intervals; there is a clear decay visible (two magnitudes within two hours), simultaneous with the observed fading in X-rays. This provides strong evidence that the fading UVOT source represents the optical counterpart of the system and allows for a sub-arcsecond localisation of the burster (Israel et al. 2008).
Figure 4.3: Images of the field around J1735. Upper left: summed X-ray image of Swift/XRT PC mode data (0.3–10 keV) obtained after the X-ray burst in 2008 (IDs 311603004–311603015). The BAT error circle and the Integral position of IGR J17353–3539 are also indicated (see Section 4.2.5). Upper right: Swift/UVOT WH-band image obtained during the X-ray burst (ID 311603000). The 3″ ROSAT/HRI error circle (see Section 4.2.4), as well as the 1.7″ Swift/XRT error circle are indicated in this image. Lower left: Magellan J-band image. The circle represents a 1σ error circle around the UVOT position. The counterpart proposed by Rodriguez et al. (2009) is also indicated (see Section 4.1). Lower right: V-band optical image obtained with the NTT.

4.2.2 Ground-based optical/near-IR photometry

All optical photometric observations discussed in this section were reduced using standard routines in IRAF\(^4\) by subtracting an average bias frame and dividing by a normalized flat field. The near-IR data was reduced using IRAF and the specific PANIC package provided by the Las Campanas Observatory.

\(^4\)IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.
4.2 Observations and data reduction

REM

The REM is a 60-cm fast slewing telescope located at la Silla, Chile, which is dedicated to prompt optical/near-IR follow-ups of GRB afterglows (Zerbi et al. 2001; Chincarini et al. 2003; Covino et al. 2004). The REM automatically responded when BAT triggered on the X-ray burst from J1735 and started observing with the ROSS camera 188 s after the BAT trigger. A series of 5 $R$-band observations with exposure times of 30 s were carried out during the X-ray burst decay and two more frames of 120 s each were obtained the next day, all in the $R$-band. These images show a source declining in brightness at a position consistent with the UVOT location. The seeing during the observations was 1.7$''$ and 1.8$''$ on 2008 May 14 and 15, respectively.

Astrometry was performed using the USNOB1.0 catalogue and aperture photometry was done with the SExtractor package (Bertin & Arnouts 1996) for all the objects in the field. The calibration was done against Landolt standard stars. In order to minimise any systematic effect, we performed differential photometry with respect to a selection of local isolated and non-saturated standard stars.

Magellan

Cackett et al. (2008b) already reported on near-IR observations of the field around J1735, carried out with the PANIC camera (Martini et al. 2004) on the 6.5-m Magellan Baade telescope. We summarise those observations here. On 2008 May 25, eleven days after the occurrence of the X-ray burst, images were acquired in the $J$, $H$- and $Ks$-bands for total on-source times of 600, 300 and 300 s, respectively. The observations were taken in a series of 5 pattern dithers; the separate images were shifted and combined in the standard way. The astrometry was tied to known 2MASS sources in the field, which were also used to calibrate the photometry of J1735.

In all three bands a source is detected at a position of $\alpha = 17^h35^m23.74^s$, $\delta = -35^\circ40'16.6''$ (J2000) with an uncertainty of 0.1$''$. Within the errors, this is consistent with the UVOT coordinates of J1735, implying that this is the possible near-IR counterpart. The lower left panel of Figure 4.3 shows the $J$-band image.

NTT

Further optical photometric observations were performed on 2008 June 16, using the EFOSC2 camera on the ESO 3.6-m NTT located at la Silla. Images were obtained in the $B$-, $V$- and $R$-waveband for total exposure times of 900, 900 and 2100 s, respectively. During these observations the seeing was varying between 0.9$''$ and 1.4$''$.

In both the $V$- and the $R$-band, a weak source is detected right at the position of

\footnote{http://www.nofs.navy.mil/data/fchpix.}
Table 4.2: Results from spectral analysis of the post-burst Swift/XRT data.

<table>
<thead>
<tr>
<th>Date</th>
<th>Mode</th>
<th>Count rate</th>
<th>$\Gamma$</th>
<th>$F_{\text{abs}}^X$</th>
<th>$F_{\text{unabs}}^X$</th>
<th>$L_X$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2008-05-15</td>
<td>WT</td>
<td>0.13</td>
<td>2.2 ± 0.3</td>
<td>0.77 ± 0.09</td>
<td>1.5 ± 0.2</td>
<td>1.6 ± 0.2</td>
</tr>
<tr>
<td>2008-05-15</td>
<td>WT</td>
<td>0.08</td>
<td>2.4 ± 0.4</td>
<td>0.51 ± 0.07</td>
<td>1.2 ± 0.3</td>
<td>1.3 ± 0.3</td>
</tr>
<tr>
<td>2008-05-28</td>
<td>PC</td>
<td>0.17</td>
<td>2.1 ± 0.2</td>
<td>1.20 ± 0.10</td>
<td>2.2 ± 0.3</td>
<td>2.4 ± 0.3</td>
</tr>
<tr>
<td>2008-06-05</td>
<td>PC</td>
<td>0.08</td>
<td>2.5 ± 0.3</td>
<td>0.53 ± 0.04</td>
<td>1.2 ± 0.2</td>
<td>1.3 ± 0.2</td>
</tr>
<tr>
<td>2008-06-14</td>
<td>PC</td>
<td>0.18</td>
<td>2.2 ± 0.2</td>
<td>1.30 ± 0.10</td>
<td>2.5 ± 0.3</td>
<td>2.7 ± 0.3</td>
</tr>
<tr>
<td>2008-07-12</td>
<td>PC</td>
<td>0.14</td>
<td>2.1 ± 0.2</td>
<td>0.92 ± 0.03</td>
<td>1.7 ± 0.2</td>
<td>1.8 ± 0.2</td>
</tr>
<tr>
<td>2008-07-28</td>
<td>PC</td>
<td>0.06</td>
<td>3.0 ± 0.6</td>
<td>0.33 ± 0.05</td>
<td>1.2 ± 0.5</td>
<td>0.7 ± 0.3</td>
</tr>
<tr>
<td>2008-07-29</td>
<td>PC</td>
<td>0.18</td>
<td>2.3 ± 0.2</td>
<td>1.10 ± 0.10</td>
<td>2.2 ± 0.3</td>
<td>2.4 ± 0.3</td>
</tr>
<tr>
<td>2008-07-31</td>
<td>PC</td>
<td>0.07</td>
<td>2.4 ± 0.8</td>
<td>0.45 ± 0.09</td>
<td>1.0 ± 0.4</td>
<td>1.1 ± 0.4</td>
</tr>
<tr>
<td>2008-08-02</td>
<td>PC</td>
<td>0.08</td>
<td>2.5 ± 0.6</td>
<td>0.42 ± 0.10</td>
<td>1.0 ± 0.3</td>
<td>1.1 ± 0.3</td>
</tr>
<tr>
<td>2008-08-05</td>
<td>PC</td>
<td>0.17</td>
<td>2.5 ± 0.3</td>
<td>0.99 ± 0.08</td>
<td>2.3 ± 0.4</td>
<td>2.5 ± 0.4</td>
</tr>
<tr>
<td>2009-07-24</td>
<td>PC</td>
<td>0.11</td>
<td>2.5 ± 0.3</td>
<td>0.73 ± 0.08</td>
<td>1.7 ± 0.2</td>
<td>1.8 ± 0.2</td>
</tr>
</tbody>
</table>

Note.– The quoted errors represent 90% confidence levels. The hydrogen column was tied between the observations; the best fit yielded $N_H = (9.3 ± 1.0) \times 10^{21}$ cm$^{-2}$ for $\chi^2 = 1.1$ (190 d.o.f.). The quoted fluxes are in the 0.5–10 keV energy range and the luminosity in that band was calculated assuming a distance of $D = 9.5$ kpc.

the near-IR source found in Magellan images. The field around J1735 was calibrated against SA110 Landolt standard field stars that were observed on the same night. We corrected the instrumental magnitudes using the average atmospheric extinction mentioned on the La Silla website.⁶

### 4.2.3 Optical spectroscopy

Through a DDT request we obtained three 1200 s long slit spectra on 2008 July 27 00:29 – 01:10 UT with the FORS2 instrument mounted on the 8.2-m VLT. We used the 600RI holographic grism, a slit width of 1.0″ and the CCD detector binned by 2 to provide a dispersion of 1.63 Å per pixel in the wavelength range $\lambda\lambda 5300 – 8600$. The observations took place under a 0.7″ seeing, yielding a spectral resolution of 220 and 160 km s$^{-1}$ at H$\alpha$ and 8500 Å, respectively.

The spectra were reduced using the IRAF KPNO/SIT package. The data were bias subtracted, flat field corrected and optimally extracted (Horne 1986). Wavelength calibration was performed using lines from He, HgCd, Ar & Ne lamp spectra obtained with the same instrumental set-up during daytime, the day after the observations – as is customary for VLT service mode observations. The extracted spectra were analysed further using the IRAF tool SPLOR and the software package MOLLY.

4.2 Observations and data reduction

4.2.4 Flux history

**ROSAT**

J1735 was discovered in 1990 September during an all sky-survey with the Position Sensitive Proportional Counter (PSPC) onboard the *ROSAT* satellite (ID RS932341). Pointed follow-up observations with the High Resolution Imager (HRI) were carried out on 1994 October 1 (ID RH900607). According to the *ROSAT* online catalogue\(^7\) the detected count rates were 0.14 ± 0.02 counts s\(^{-1}\) for the PSPC and 0.021 ± 0.004 counts s\(^{-1}\) for the HRI (0.1–2.5 keV).

Employing \(\text{\textsc{pmms}}\) and adapting the spectral parameters found for the persistent X-ray emission of J1735 (see Section 4.3.1; \(N_\text{H} = 9.3 \times 10^{21} \text{ cm}^{-2}\) and a powerlaw index \(\Gamma = 2.3\)), this translates into 0.5–10 keV unabsorbed fluxes of \((1.8 \pm 0.3) \times 10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1}\) and \((7.2 \pm 1.4) \times 10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1}\), for the PSPC and HRI, respectively. The corresponding *Swift/XRT* PC mode count rates are 0.18 ± 0.03 and 0.07 ± 0.01 counts s\(^{-1}\), consistent with the persistent emission detected with *Swift/XRT* in 2008 and 2009 (see Figure 4.2 and Table 4.2).

**XMM-Newton**

In addition to the above mentioned *ROSAT* detections, J1735 was observed with *XMM-Newton* on 2008 March 4, which is 10 weeks prior to the X-ray burst caught by *Swift*, as part of the *XMM-Newton* slew survey (Read et al. 2005).\(^8\) The source was detected with the European Photon Imaging Camera (EPIC) PN instrument at a count rate of 2.24 ± 0.53 counts s\(^{-1}\) (0.2–12 keV), which converts into a 0.5–10 keV unabsorbed flux of \(\sim (4 \pm 1) \times 10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1}\) (again using \(\text{\textsc{pmms}}\) with \(N_\text{H} = 9.3 \times 10^{21} \text{ cm}^{-2}\) and a powerlaw index \(\Gamma = 2.3\)). The corresponding *Swift/XRT* count rate is \(\sim 0.40 \pm 0.10\) counts s\(^{-1}\).

4.2.5 Searches for other X-ray bursts

**Integral**

J1735 lies within the 3′ error box of the unclassified hard X-ray source IGR J17353–3539 (see Figure 4.3; this coincidence was also noted by Rodriguez et al. 2009), which appears in the *Integral* all-sky survey catalogue (Krivonos et al. 2007; Bird et al. 2010). We used the publicly available *Integral* data to search for X-ray bursts from the location of J1735/IGR J17353–3539. This region has been covered by reg-

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\(^7\)http://www.xray.mpe.mpg.de/cgi-bin/rosat/src-browser.

\(^8\)J1735 appears in the third update of the catalogue, which was released in July 2009, and is assigned the name XMMSL1 J173524.0–354021.
ular observations of the *Integral* satellite (Winkler et al. 2003) since the beginning of 2003, in particular at low energy (3–20 keV) with the Joint European X-ray Monitor (JEM-X; Lund et al. 2003), module 1 and 2, and at high energies (17–100 keV) with the *Integral* Soft Gamma-ray Imager (ISGRI; Lebrun & et al. 2003), mounted on the Imager onBoard the *Integral* Satellite (IBIS; Ubertini et al. 2003). The data are divided into individual pointings called Science Windows (ScW), themselves grouped into revolutions of the satellite. *Integral* was not pointing towards the source field when the X-ray burst picked up by BAT occurred.

In the archival public data, there are 7359 IBIS ScW between revolutions 37 and 674, pointing less than 12 degrees from the source, and 650 JEM-X ScW between revolutions 46 and 661, pointing less than 3.5 degrees from the source. These data are spread over a time range of five years, from 2003 February 1 to 2008 April 20, for effective exposures of 16 and 0.76 Ms for IBIS and JEM-X, respectively. The difference of exposure is due to the fact that IBIS has a larger field of view than JEM-X and thus happened to observe IGR J17353–3539 more often.

We have analysed this data set with the standard Offline Science Analysis software (OSA; v.7.0), distributed by the *Integral* Science Data Center (ISDC; Courvoisier et al. 2003) and based on algorithms described in Goldwurm et al. (2003) for IBIS and Westergaard et al. (2003) for JEM-X. The total collapsed mosaic of the IBIS images reveals a weak but significant (7.7σ) excess at the position of the source. Its flux in the 17–40 keV band is \( \sim 4 \times 10^{-12} \) erg cm\(^{-2}\) s\(^{-1}\). We have searched for X-ray bursts in the IBIS data with the *Integral* Burst Alert System (IBAS; Mereghetti et al. 2003), yet no X-ray burst was detected. We have also explored the JEM-X data, more suitable to look for such events since these are usually soft. However, again, no X-ray burst was found.

**Swift/BAT**

We investigated the *Swift/BAT* transient monitor results of J1735, provided by the *Swift/BAT* team.\(^9\) No other X-ray bursts are detected with a limiting flux of \( \sim 1.4 \times 10^{-9} \) erg cm\(^{-2}\) s\(^{-1}\) (15–50 keV) for a single pointing (which have a mean duration \( \sim 700 \) s). However, the energy range of the BAT transient monitor (15–50 keV) is not optimally sensitive to X-ray bursts as soft as the May 14 event and it is therefore possible that an X-ray burst brighter than \( \sim 1.4 \times 10^{-9} \) erg cm\(^{-2}\) s\(^{-1}\) has been missed in this wider band. During the five years of the *Swift* mission there have been no other onboard triggers comparable in intensity to the X-ray burst of 2008 May 14. The total BAT exposure time till 2009 August 5 is 4.3 Ms.

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\(^9\)See http://swift.gsfc.nasa.gov/docs/swift/results/transients/weak/1RXHJ173523.7–354013.
4.3 Results

4.3.1 Persistent X-ray emission

The post-burst data taken with Swift/XRT (see Table 4.2 for an overview) was modelled with an absorbed powerlaw continuum modified by absorption (pabs; we used the default Xspec abundances and cross section for this model). We fitted all spectra simultaneously with the hydrogen column density tied between all observations. The results of this simultaneous modelling, which yielded a final $\chi^2_\nu = 1.1$ for 190 degrees of freedom (d.o.f.), are presented in Table 4.2. The values of the spectral parameters were not significantly different when each observation was fit separately.

The best fit hydrogen column density is $N_H = (9.3 \pm 1.0) \times 10^{21} \text{ cm}^{-2}$ and the powerlaw index is consistent with being constant within the spectral errors (the average value is $\Gamma = 2.3 \pm 0.2$). In the days–months following the X-ray burst the source settled at an average unabsorbed flux of $F_X^{\text{unabs}} \sim 1.9 \times 10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1}$ (0.5–10 keV), varying by a factor of $\sim 2$. Assuming a bolometric correction factor of 2 (in’t Zand et al. 2007), we estimate a bolometric persistent flux of $F_{\text{bol}}^{\text{pers}} \sim 3.8 \times 10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1}$ (0.01–100 keV), which equals $\sim 0.1$ per cent of Eddington for a distance of 9.5 kpc.
4.3.2 X-ray burst

Spectra and lightcurve

We fitted the BAT (15–35 keV) and XRT (0.5–10 keV) X-ray burst spectra with an absorbed blackbody model `bbodyrad`, which has a normalization that equals $R_{bb}^2 / D_{10}^2$, where $R_{bb}$ is the emitting radius in km and $D_{10}$ is the source distance in units of 10 kpc. We kept the hydrogen column density fixed at the value found from fitting the persistent emission spectra ($N_{H} = 9.3 \times 10^{21} \text{ cm}^{-2}$). Since the last two XRT data segments trace the faint end of the X-ray burst, the underlying persistent emission must be taken into account. Therefore, we add a powerlaw component in the spectral fits, for which the index and normalization are fixed at the average values found from modelling the persistent emission (see Section 4.3.1). To estimate the bolometric fluxes during the X-ray burst, we extrapolate the fitted blackbody component to the 0.01–100 keV energy range. For the BAT data we find a blackbody temperature of $kT_{bb} = 2.3^{+0.5}_{-0.4}$ keV and an unabsorbed 0.01–100 keV flux of $F_{\text{bol}} = 3.5^{+5.0}_{-1.7} \times 10^{-8} \text{ erg cm}^{-2} \text{ s}^{-1}$.

X-ray bursts picked up by BAT are typically the most energetic bursts, which frequently show photospheric radius-expansion (PRE) indicating that the Eddington luminosity is reached during the burst peak. However, the low number of counts in the BAT data and the gap with the XRT observations preclude a spectral confirmation of such an expansion (i.e., a local peak in emitting radius associated with a dip in blackbody temperature). If we assume that the peak flux was equal to or lower than that typical of PRE bursts ($3.8 \times 10^{38} \text{ erg s}^{-1}$; Kuulkers et al. 2003), we can place an upper limit on the source distance of $D \lesssim 9.5$ kpc. However, for a
4.3 Results

H-rich photosphere (H-fraction X=0.7), the empirically derived Eddington limit is 1.6 \times 10^{38} \text{ erg s}^{-1} (Kuulkers et al. 2003) and this would lower the distance estimate to $D \lesssim 6.2 \text{ kpc}$. In this work we have adopted a distance of 9.5 kpc when calculating luminosities, energies and blackbody emitting radii.

The results from our time-resolved spectroscopic analysis of the BAT and XRT data are presented in Table 4.3 and Figure 4.5. The 0.01–100 keV flux decreases by 2 orders of magnitude from $F_{\text{peak}}^{\text{bol}} \sim 3.5 \times 10^{-8} \text{ erg cm}^{-2} \text{ s}^{-1}$ at the time of the BAT trigger down to $F_{\text{bol}} \sim 1.0 \times 10^{-10} \text{ erg cm}^{-2} \text{ s}^{-1}$ in the final XRT data interval, which was obtained 1.6 h after the burst trigger. The blackbody temperature decreases from $kT_{\text{bb}} \sim 2.3 \text{ keV}$ at the peak down to $kT_{\text{bb}} \sim 0.6 \text{ keV}$ in the tail of the X-ray burst.

Based on theoretical modelling, the flux in the cooling tails of long X-ray bursts is expected to follow a powerlaw decay (Cumming & Macbeth 2004). The XRT light curve data, representing the burst tail, can be fit with a simple powerlaw with index $-1.53 \pm 0.03$ and a normalization of $(5.3 \pm 1.0) \times 10^{-5} \text{ erg cm}^{-2} \text{ s}^{-1}$ ($\chi^2 = 1.0$ for 2 d.o.f.). Extrapolating this fit down to the level of the persistent emission ($F_{\text{pers}}^{\text{bol}} \sim 3.8 \times 10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1}$), we can estimate a burst duration of $\sim 8000 \text{ s}$ ($\sim 2.2 \text{ h}$; see Figure 4.4). A single exponential decay does not provide an adequate fit to the tail of the X-ray burst ($\chi^2 \approx 8$ for 3 d.o.f.).

**Energetics and ignition conditions**

The X-ray burst was visible in the BAT lightcurve for $\sim 200 \text{ s}$ and we estimated a bolometric flux of $\sim 3.5 \times 10^{-8} \text{ erg cm}^{-2} \text{ s}^{-1}$ from the BAT spectrum (see Table 4.3). This implies a fluence of $f_{\text{BAT}} \sim 7 \times 10^{-6} \text{ erg cm}^{-2}$ for the BAT data. To estimate the fluence in the burst tail, we integrate the XRT data along the above described powerlaw decay from $t = 100 \text{ s}$ (the time at which the burst peak had disappeared from the BAT lightcurve) till $t = 8000 \text{ s}$ after the burst trigger (when the flux had decayed down to the persistent level). This way we find a bolometric fluence of $f_{\text{XRT}} \sim 7.7 \times 10^{-6} \text{ erg cm}^{-2}$. The total estimated bolometric fluence of the X-ray burst thus adds up to $f_{\text{burst}} \sim 1.5 \times 10^{-5} \text{ erg cm}^{-2}$. Using the distance upper limit of 9.5 kpc, this implies a maximum radiated energy of $E_{\text{burst}} \lesssim 1.6 \times 10^{41} \text{ erg}$. This is more energetic than typical type-I X-ray bursts (see Section 4.4).

Using the observed burst energetics, we can calculate the depth at which the X-ray burst ignited. The ignition column depth is given by $y = E_{\text{burst}} (1 + z)/4\pi R^2 Q_{\text{nuc}}$, where $z$ is gravitational redshift, $R$ is the neutron star radius and $Q_{\text{nuc}} = 1.6 + 4X$ MeV nucleon$^{-1}$ the nuclear energy release given a H-fraction X at ignition (e.g., Galloway et al. 2008a). Assuming a neutron star with $M = 1.4 \text{ M}_\odot$ and $R = 10 \text{ km}$ (so that $z = 0.31$), we find an ignition depth of $y \sim 1.5 \times 10^{10} \text{ g cm}^{-2}$ for pure He (X=0) or $y \sim 5.4 \times 10^{9} \text{ g cm}^{-2}$ for solar abundances (X=0.7).

Next we can estimate the recurrence time that corresponds to these ignition depths.
A distance of $D \lesssim 9.5$ kpc would convert the bolometric persistent flux (see Section 4.3.1) into a luminosity of $L_{\text{bol}}^{\text{pers}} \lesssim 4.1 \times 10^{35}$ erg s$^{-1}$. For a neutron star of mass $M = 1.4$ M$_{\odot}$ and radius $R = 10$ km this implies a global mass-accretion rate of $\dot{M} \sim RL_{\text{bol}}^{\text{pers}} / GM \lesssim 3.6 \times 10^{-11}$ M$_{\odot}$ yr$^{-1}$ ($\sim 0.1\%$ of the Eddington rate). Assuming isotropy, this corresponds to a local accretion rate (i.e., per unit area) of $\dot{m} \lesssim 1.7 \times 10^2$ g cm$^{-2}$ s$^{-1}$. Given this local accretion rate and the ignition conditions calculated above, we can estimate the time required to build up the layer that caused the X-ray burst observed from J1735. We find $t_{\text{rec}} \sim y(1 + z)/\dot{m} \gtrsim 3.7$ yr (X=0) or 1.3 yr (X=0.7). Such a long recurrence time is consistent with the fact that no other X-ray bursts were detected in the entire sample of Integral observations (JEM-X and IBIS/ISGR; 16.8 Ms) and the Swift/BAT transient monitor (4.3 Ms).

### 4.3.3 Optical/near-IR photometry

Table 4.4 summarises the results from optical and near-IR photometry carried out with different instruments. During the X-ray burst, three UVOT $WH$-filter images were obtained, which show a clear fading from a magnitude of $18.6 \pm 0.1$, 154 s after the burst trigger, down to $20.9 \pm 0.3$ mag more than an hour later (see Figure 4.4).
The REM telescope acquired two series of R-band images. The first (starting 188 s after the BAT trigger) was carried out during the decay of the X-ray burst and clearly detected the source at $R = 15.9 \pm 0.2$. During the second set of observations obtained one day later, no source could be detected with a limiting magnitude of $R > 17.5$, indicating that the R-band flux had faded by $> 1.5$ mag. This result is consistent with the decrease in flux observed in the X-ray band.

Within a month after the BAT detection of the X-ray burst from J1735, optical and near-IR observations were obtained to characterise the persistent emission of the system. In the J-, H- and Ks-band images obtained with Magellan, a source consistent with the UVOT position of J1735 was detected (see Figure 4.3). The NTT observations detected a possible optical counterpart in both the V- (see Figure 4.3) and R-band, but no source was detected in the B-band. The R-band magnitude derived from the NTT observations is consistent with the upper limit obtained from the REM images. The observed apparent magnitudes and colours are listed in Table 4.4.

Using the hydrogen absorption column found from fitting the spectral X-ray data ($N_H = 9.3 \times 10^{21}$ cm$^{-2}$), we can calculate the visual extinction. We use the standard relation $N_H/A_V = (1.79 \pm 0.03) \times 10^{21}$ atoms cm$^{-2}$ mag$^{-1}$, which yields $A_V = 5.2 \pm 0.6$ mag (Predehl & Schmitt 1995). The extinction in the other bands can be estimated using the relations $A_B/A_V = 1.325$, $A_R/A_V = 0.748$, $A_J/A_V = 0.282$, $A_H/A_V = 0.175$ and $A_K/A_V = 0.112$ (Rieke & Lebofsky 1985). The de-reddened magnitudes and colours are also listed in Table 4.4.

### 4.3.4 Optical spectra

The VLT spectra reveal several features, the most prominent being H$\alpha$ in emission above the continuum (see Figure 4.6). A single Gaussian fit is a good representation of the line profile, yielding a full width at half maximum (FWHM) of $292 \pm 9$ km s$^{-1}$. The fits show that the line profile is blue-shifted $-58 \pm 4$ km s$^{-1}$ with respect to the rest wavelength, and no Doppler shifts in the central wavelength are seen between the three VLT spectra (which were obtained in an interval of one hour). The line has an equivalent width (EW) of $-9.0 \pm 0.4$ Å.

The bottom plot of Figure 4.6 displays the region around the Ca$\text{III}$ triplet (the redder component of the triplet falls outside the range covered by the detector). From a single Gaussian fit to the Ca$\text{III}$ lines at 8498.02 and 8542.09 Å, we find a blue shift of $-67 \pm 12$ km s$^{-1}$ and a FWHM$=276 \pm 12$ km s$^{-1}$. In addition, we detect O$\text{I}$ at 8446 Å. The narrow feature next to it at $\sim 8450$ Å is likely a cosmic ray as it appears in only one of the three spectra. The feature at $\sim 8590$ Å could possibly be P$\text{I}$4 emission, although it seems to be too broad and the central wavelength does not agree with the shift observed for the other lines. The identification of this feature is therefore uncertain.
Table 4.4: Apparent magnitudes and colours derived from optical/near-IR photometry.

<table>
<thead>
<tr>
<th>Date</th>
<th>Band</th>
<th>Observed magnitude</th>
<th>De-reddened magnitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>X-ray burst</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2008-05-14</td>
<td>WH</td>
<td>18.6 ± 0.1</td>
<td></td>
</tr>
<tr>
<td>2008-05-14</td>
<td>WH</td>
<td>20.2 ± 0.2</td>
<td></td>
</tr>
<tr>
<td>2008-05-14</td>
<td>WH</td>
<td>20.9 ± 0.3</td>
<td></td>
</tr>
<tr>
<td>2008-05-14</td>
<td>R</td>
<td>15.9 ± 0.2</td>
<td>11.7 ± 0.5</td>
</tr>
<tr>
<td>Persistent emission</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2008-05-15</td>
<td>R</td>
<td>&gt; 17.5</td>
<td>&gt; 13.6</td>
</tr>
<tr>
<td>2008-06-16</td>
<td>B</td>
<td>&gt; 23</td>
<td>&gt; 16.1</td>
</tr>
<tr>
<td>2008-06-16</td>
<td>V</td>
<td>21.2 ± 0.1</td>
<td>16.0 ± 0.6</td>
</tr>
<tr>
<td>2008-06-16</td>
<td>R</td>
<td>18.8 ± 0.1</td>
<td>14.9 ± 0.5</td>
</tr>
<tr>
<td>2008-05-25</td>
<td>J</td>
<td>15.4 ± 0.1</td>
<td>13.9 ± 0.2</td>
</tr>
<tr>
<td>2008-05-25</td>
<td>H</td>
<td>14.3 ± 0.1</td>
<td>13.4 ± 0.1</td>
</tr>
<tr>
<td>2008-05-25</td>
<td>K</td>
<td>13.8 ± 0.1</td>
<td>13.2 ± 0.1</td>
</tr>
<tr>
<td>Colours</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2008-06-16</td>
<td></td>
<td>0.0 ≤ (V − R)_0 ≤ 2.2</td>
<td></td>
</tr>
<tr>
<td>2008-06-16</td>
<td></td>
<td>(B − V)_0 ≤ −0.5</td>
<td></td>
</tr>
<tr>
<td>2008-05-25</td>
<td></td>
<td>0.2 ≤ (J − H)_0 ≤ 0.8</td>
<td></td>
</tr>
<tr>
<td>2008-05-25</td>
<td></td>
<td>0.0 ≤ (H − K)_0 ≤ 0.4</td>
<td></td>
</tr>
</tbody>
</table>

Note.– The quoted errors and upper limits for the magnitudes represent 1σ and 3σ confidence levels, respectively. The de-reddened colours represent a 1σ range.

The main interstellar features are the sodium doublet at 5890 and 5896 Å and interstellar bands at 5780 and 6284 Å. Furthermore, an absorption is observed at 6495 Å with an EW = 1.5 ± 0.2 Å (see Figure 4.6). This feature is observed in late-type stars and is due to a blend of metallic absorption lines. However, we do not expect to observe photospheric lines in the spectrum of J1735, as the accretion disc is likely to dominate the optical flux – no other strong metallic lines are observed in the spectrum. A similar feature has been reported in the optical spectrum of the X-ray transient XTE J1118+480 during outburst, which was tentatively associated to cool emitting regions in the accretion flow (see Torres et al. 2002).

4.4 Discussion

In this paper we presented X-ray, optical and near-IR observations of the previously unclassified ROSAT source J1735. This system was the likely origin of a Swift/BAT trigger that occurred on 2008 May 14 and we carried out a multi-wavelength observing campaign to get a more complete picture of the properties of this X-ray source.
4.4 Discussion

Figure 4.6: Close-ups of the averaged VLT spectra. Left: region around Hα. Right: region around the Ca II triplet. The feature labelled ‘CR’ denotes a likely cosmic ray event.

4.4.1 The optical/near-IR counterpart

We investigated all the XRT and UVOT data that were obtained within two hours after the BAT trigger. The XRT spectra could be successfully modelled by blackbody radiation and revealed cooling during the decay, which confirms that this was a thermonuclear event. This testifies that J1735 contains an accreting neutron star and classifies the system, in all likelihood, as an LMXB. The UVOT WH-band images revealed an optical source that was fading simultaneously with the observed decrease in X-ray flux. Such behaviour is typical of type-I X-ray bursts and is thought to result from reprocessing of X-rays (e.g., Lewin et al. 1995). This provides strong evidence that the fading UVOT source is the counterpart of J1735. A similar fading was detected in R-band images obtained with the REM telescope.

Using the NTT, Magellan and VLT, we detect an optical/near-IR source within the UVOT positional uncertainty of J1735. The VLT observations reveal a spectrum with a single-peaked Hα emission line. Such emission is typical for X-ray binaries, accreting white dwarfs and Be stars. The broadband colours of the counterpart after correcting for the reddening are not consistent with a Be star, which has a bluer spectral energy distribution (SED) than observed (cf. Section 4.3.3 and Drilling & Landolt 2000; Tokunaga 2000). This effectively rules out the possibility that we detect a Be star interloper within the UVOT error circle. Thus, we conclude that we have detected the optical/near-IR counterpart of J1735.

The Hα and Ca II emission line broadening observed in the VLT spectra is strongly affected by the instrumental profile, which makes it difficult to assess whether or not the lines are double-peaked. We subtract in quadrature the instrumental width to find a FWHM of $192 \pm 9$ and $225 \pm 12$ km s$^{-1}$ for the Hα and Ca II lines, respectively (see...
Section 4.3.4). The ratio of these FWHMs are consistent with the ratio of the rest wavelengths and thereby with Doppler broadening of the line.

The observed EW and intrinsic FWHM of the lines match two possible scenarios for the origin of the line emission. The first is that the emission arises from the accretion disc, in which case the line profile would be double-peaked unless the system is viewed face-on (e.g., Huang 1972). In the second scenario, the emission is due to X-ray reprocessing in the hemisphere of the secondary facing the neutron star, which would produce a single-peaked profile (e.g., Bassa et al. 2009). Further spectroscopic observations at higher spectral resolution may test these hypotheses.

### 4.4.2 The type-I X-ray burst

The parameters of the X-ray burst from J1735, as inferred from spectral analysis of the BAT and XRT data, are summarised in Table 4.5. These show that it was no ordinary type-I X-ray burst, which are triggered by unstable burning of H/He and typically last ~ $10 - 100$ s releasing a total energy of ~ $10^{39-40}$ erg. Yet it is not as energetic as the so-called superbursts, which endure for many hours and are thought to be fuelled by carbon rather than H/He, resulting in a total energy release of ~ $10^{42-43}$ erg (e.g., Strohmayer & Bildsten 2006). Instead, the duration (~ 2 h) and total energy output ($E_{\text{burst}} \lesssim 1.5 \times 10^{41}$ erg) suggest that the X-ray burst from J1735 belongs to the rare class of intermediately long X-ray bursts. The driving mechanism behind these events is thought to be the ignition of a thick layer of He and their host systems probe unusual accretion regimes (in’t Zand et al. 2005a, 2007; Cumming et al. 2006).

Several intermediately long X-ray bursts have been detected from (candidate) ultra-compact X-ray binaries (UCXBs; see e.g., in’t Zand et al. 2005a, 2008; Falanga et al. 2008; Kuulkers et al. 2010). These systems have orbital periods $\lesssim 80$ min, which implies that the donor star must be H-deficient (Nelson et al. 1986). In this context, the intermediately long bursts are explained in terms of the neutron stars accreting He-rich material. However, in case of J1735 the detection of strong H$\alpha$ emission in the spectrum of the optical counterpart strongly indicates that the donor star in J1735 is H-rich and that the neutron star is not accreting pure He.

There are a few other systems displaying intermediately long type-I X-ray bursts for which there are indications that the accreted matter contains H (Chenevez et al. 2007; Linares et al. 2009b; Falanga et al. 2009). Peng et al. (2007) study the accretion of H-rich material at low accretion rates, and demonstrate that there exists a narrow regime, spanning only a factor of ~ 3 in mass-accretion rate, for which H flashes occur that are too weak to ignite He. For accretion rates lower than this range, the rise in temperature following a H flash is sufficient to cause He ignition, resulting in a short, mixed H/He burst (Peng et al. 2007). These authors speculate that a series of weak H
flashes might build up a large reservoir of He that produces a long X-ray burst, like the ones observed for UCXBs, once it ignites. This behaviour is confirmed by the theoretical models of Cooper & Narayan (2007) and might provide the framework to explain the intermediately long X-ray burst observed from J1735.

Peng et al. (2007) find that unstable H burning can accumulate a thick layer of He for a regime of local mass-accretion rates of 0.3–1% of the Eddington rate, which is higher than what we infer for J1735 ($\dot{m} \lesssim 0.1\%$ of Eddington; see Section 4.3.2). However, the boundary values of this narrow range are sensitive to the heat flux emerging from the neutron star crust, which results from a series of non-equilibrium reactions induced by the accretion of matter (see e.g., Haensel & Zdunik 2008, and references therein). At low accretion rates, this heat flow largely sets the thermal structure of the accreted layer and thereby the ignition conditions for X-ray bursts.

To explain the occurrence of intermediately long X-ray bursts from systems accreting around 1% of Eddington, Peng et al. (2007) choose a heat release of 0.1 MeV per accreted nucleon. If this value is increased to 1.0 MeV, as may be better justified for the low accretion rates under consideration (Brown 2004), the range allowing for intermediately long bursts decreases to $\dot{m} \sim 0.03–0.1\%$ of Eddington, i.e., consistent with the value we infer for J1735. Nevertheless, for this combination of heat release and $\dot{m}$, the expected ignition column depth is much higher than observed for J1735 (see figure 11 of Peng et al. 2007).

Achieving ignition at $y \lesssim 1.5 \times 10^{10}$ g cm$^{-2}$, requires either that the heat deposited in the crust is more than 1.0 MeV per accreted nucleon (which may be reasonable, see e.g., Haensel & Zdunik 2008), or that the local mass-accretion rate is actually higher than what we infer for J1735. While we assumed isotropy, it is also possible that the accretion flow is concentrated onto a small area of the neutron star surface, in which case the local mass-accretion rate is underestimated. However, the apparent mismatch between the observations of J1735 and the theoretical calculations might also be due to limitations of the simplified model description (Peng et al. 2007).

We note that the properties of the X-ray burst of J1735 are very similar to the intermediately long bursts from XTE J1701–462 (Linares et al. 2009b; Falanga et al. 2009) and 4U 1246–58 (in’t Zand et al. 2008), which both triggered the BAT and were subsequently observed by the XRT. The three X-ray bursts have similar BAT rise times of tens of seconds and we found that the XRT tails show comparable decay rates. Yet the nature of the three systems seems to be very different. XTE J1701–462 is known to be a transient system, albeit it is exhibiting a prolonged accretion outburst that started in 2008 June and is ongoing at the time of writing (the intermediately long burst was detected 5 weeks after the onset of the outburst; e.g., Linares et al. 2009b). 4U 1246–58, on the other hand, is persistently accreting and is proposed to be an
UCXB based on its low optical magnitude and the absence of Hα emission in the source spectrum (Bassa et al. 2006). Both systems accreted at a level of ~1% of the Eddington rate when the intermediate long X-ray bursts occurred. J1735 seems to be a persistent system (see Section 4.4.3) accreting from a H-rich donor at ~0.1% of the Eddington rate, which is a factor of 10 lower than inferred for the other two sources.

4.4.3 The nature of 1RXH J173523.7–354013

J1735 was detected with ROSAT in 1990 and 1994, with XMM-Newton in 2008 March, and the source field was covered several times with Swift between 2008 May–August, as well as during a single pointing in 2009 July. On all occasions the source displayed similar unabsorbed fluxes of ~ (1–4) × 10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1} (0.5–10 \text{ keV}), which indicates that J1735 is a persistent, rather than transient, LMXB. The long burst recurrence time confirms that the system is intrinsically faint and accreting at low rates. The persistent nature at a low accretion luminosity suggests the possibility of a relatively small orbit. Small accretion discs are easier to be kept photo-ionized completely, thereby sustaining the accretion and avoiding the disc instability model that would make the system transient. Based on this argument, in’t Zand et al. (2007) use a low persistent flux as a diagnostic to put forward several candidate UCXBs, drawn from the total sample of bursting, persistent LMXBs. However, our optical data suggests that J1735 is likely not an UCXB.

As already mentioned above, the detection of strong Hα emission in the spectrum of the optical counterpart strongly indicates that the donor star in J1735 is H-rich, effectively ruling out the UCXB scenario. Furthermore, the absolute visual magnitude (M_V) of J1735 can be estimated using the distance modulus. For a de-reddened apparent magnitude of V = 16.0 and a distance D \lesssim 9.5 \text{ kpc} (inferred from the peak of the X-ray burst), we find an absolute visual magnitude of M_V \gtrsim 1.1 \text{ mag}. For the estimated mass-accretion rate of J1735 (0.1% of Eddington, see Section 4.3.2), the empirical relation derived by van Paradijs & McClintock (1994) predicts an absolute visual magnitude of M_V \gtrsim 4.8 \text{ mag} in case the system is an UCXB (assuming P_{orb} \lesssim 80 \text{ min}). Unless J1735 is located at a distance D \lesssim 2 \text{ kpc}, it is thus too optically bright to be an UCXB.

To be able to harbour a H-rich companion, J1735 must have an orbital period of \gtrsim 80 \text{ min} (e.g., Nelson et al. 1986). In such a configuration, it will be challenging to understand how the low X-ray luminosity can keep the accretion ongoing making the system persistent rather than transient.
Table 4.5: X-ray burst and persistent emission parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>X-ray burst BP rise time (s)</td>
<td>(~100)</td>
</tr>
<tr>
<td>Duration (h)</td>
<td>(~2.2)</td>
</tr>
<tr>
<td>Peak flux, $F_{\text{bol}}$ (\text{erg cm}^{-2} \text{s}^{-1})</td>
<td>(~3.5 \times 10^{-8})</td>
</tr>
<tr>
<td>Fluence, $F_{\text{burst}}$ (\text{erg cm}^{-2})</td>
<td>(~1.5 \times 10^{-5})</td>
</tr>
<tr>
<td>Distance, $D$ (kpc)</td>
<td>(\leq 9.5)</td>
</tr>
<tr>
<td>Total radiated energy, $E_{\text{burst}}$ (\text{erg})</td>
<td>(~1.6 \times 10^{44})</td>
</tr>
<tr>
<td>Ignition depth, $y$ (g cm(^{-2}))</td>
<td>(\leq 1.5 \times 10^{10})</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Persistent emission</th>
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</thead>
<tbody>
<tr>
<td>Flux, $F_{\text{bol}}$ (\text{erg cm}^{-2} \text{s}^{-1})</td>
<td>(~3.8 \times 10^{-11})</td>
</tr>
<tr>
<td>Luminosity, $L_{\text{bol}}$ (\text{erg s}^{-1})</td>
<td>(~4.1 \times 10^{35})</td>
</tr>
<tr>
<td>Global accretion rate, $M$ (M_{\odot} \text{yr}^{-1})</td>
<td>(~3.6 \times 10^{-11})</td>
</tr>
<tr>
<td>Local accretion rate, $\dot{m}$ (g cm(^{-2}) \text{s}^{-1})</td>
<td>(~1.7 \times 10^2)</td>
</tr>
</tbody>
</table>

Note.– The quoted fluxes are unabsorbed and for the 0.01–100 keV energy range. The burst duration is specified as the time from the BAT peak till the flux decayed back to the persistent level as observed with the XRT.

Acknowledgments
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The behaviour of subluminous X-ray transients near the Galactic centre as observed using the X-ray telescope aboard Swift

N. Degenaar and R. Wijnands

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Abstract – In this paper we report on the spectral analysis of seven X-ray transients, which were found to be active during a monitoring campaign of the Galactic centre carried out in 2006–2007, using the X-ray telescope aboard the Swift satellite. This campaign detected new outbursts of five known X-ray transients and discovered two new systems. Their 2–10 keV peak luminosities range from $\sim 10^{34}$ to $6 \times 10^{36}$ erg s$^{-1}$. Two of the sources discussed in this paper are confirmed neutron star systems (AX J1745.6–2901 and GRS 1741–2853), while the five others have an unknown nature. We discuss the characteristics of the observed outbursts and the duty cycles of the various systems. We detected two type-I X-ray bursts with a duration of 50–60 s from AX J1745.6–2901, which we discuss in view of the bursting behaviour of low-luminosity X-ray transients. Assuming that we are dealing with accreting neutron stars and black holes, we estimate the time-average accretion rate, $\langle \dot{M}_{\text{long}} \rangle$, of the transients, which is an important input parameter for binary evolution calculations. Our estimates lie in the range of $3 \times 10^{-13}$ M$_{\odot}$ yr$^{-1} \leq \langle \dot{M}_{\text{long}} \rangle \leq 1 \times 10^{-10}$ M$_{\odot}$ yr$^{-1}$, if the systems are neutron star X-ray binaries and between $4 \times 10^{-14}$ M$_{\odot}$ yr$^{-1} \leq \langle \dot{M}_{\text{long}} \rangle \leq 2 \times 10^{-11}$ M$_{\odot}$ yr$^{-1}$ for a scenario where the accreting object is a black hole.
5 Swift observations of subluminous X-ray transients located near the Galactic centre

5.1 Introduction

Our Galaxy harbours many X-ray transients that spend most of their time in a dim, quiescent state, but occasionally they experience bright X-ray outbursts (typically lasting weeks to months) during which their X-ray luminosity increases by more than a factor of 100. Many of these transient X-ray sources can be identified with compact objects (neutron stars or black holes) accreting matter from a companion star. In such systems, the X-ray outbursts are ascribed to a sudden strong increase in the accretion rate onto the compact object. X-ray transients can be classified based on their 2–10 keV peak luminosity, $L_{\text{peak}}^X$. The bright X-ray transients ($L_{\text{peak}}^X \sim 10^{37}$–$10^{39}$ erg s$^{-1}$) have been known and extensively studied since the early days of X-ray astronomy. However, in the past decade it became clear that a group of subluminous X-ray transients ($L_{\text{peak}}^X \lesssim 10^{37}$ erg s$^{-1}$) also exists, where the distinction is made between faint ($L_{\text{peak}}^X \sim 10^{36}$–$10^{37}$ erg s$^{-1}$, e.g., Heise et al. 1999; in’t Zand 2001) and very-faint ($L_{\text{peak}}^X \sim 10^{34}$–$10^{36}$ erg s$^{-1}$, e.g., Sidoli et al. 1999; Porquet et al. 2005b; Muno et al. 2005b; Wijnands et al. 2006a) systems. Although the faint to very faint X-ray transients exhibit qualitatively different behaviour than the brighter systems (e.g., Cornelisse et al. 2002; Okazaki & Negueruela 2001; King 2000), this classification based on peak luminosities is not strict and hybrid systems are known to exist (e.g., Wijnands et al. 2002b).

In particular the study of very-faint X-ray transients (VFXTs) is hampered by the sensitivity limitations of X-ray instruments, and consequently their nature is not understood well. To date, about 30 members are known, most of which are found very close to Sgr A* (within $\sim 10'$; Muno et al. 2005b), but this might be a selection effect due to all the high-resolution X-ray observations in this region. Several VFXTs were found at larger distances from Sgr A* as well (e.g., Hands et al. 2004; Heinke et al. 2009a). A significant fraction ($\sim 1/3$) of the VFXTs have exhibited type-I X-ray bursts (e.g., Cornelisse et al. 2002) and can thus be identified with neutron stars accreting matter from, most likely, a low-mass (i.e., $M \lesssim 1\,M_\odot$) companion. The low outburst luminosities characteristic of VFXTs combined with what is known about their duty cycles, imply that these low-mass X-ray binaries (LMXBs) have very low time-averaged mass accretion rates, which could challenge our understanding of their evolution (King & Wijnands 2006).

There might also be other types of sources that can produce subluminous X-ray outbursts. It is conceivable that some systems are compact objects that are transiently accreting at a very low level from the strong stellar wind of a high-mass star or the circumstellar matter around a Be star (e.g., Okazaki & Negueruela 2001). In addition,

\(^1\)All fluxes and luminosities quoted in this paper are for the 2–10 keV energy band, unless otherwise stated.
some strongly magnetised neutron stars ($B \sim 10^{14} - 10^{15}$ G, magnetars) are observed to experience occasional X-ray outbursts with peak luminosities of $\sim 10^{35}$ erg s$^{-1}$ (Ibrahim et al. 2004; Muno et al. 2007a) and can thus be classified as VFXTs. The cause of their outbursts is unknown, but is likely related to magnetic field decay (e.g., Ibrahim et al. 2004). Furthermore, Mukai et al. (2008) recently pointed out that classical novae can be visible as 2–10 keV X-ray sources with luminosities in the range of a few times $10^{34} - 10^{35}$ erg s$^{-1}$ for weeks to months (see figure 1 of Mukai et al. 2008). The X-ray emission is thought to emerge from shocks within the matter that is ejected during the nova.

Here we present the analysis of seven X-ray transients, that were found active during a monitoring campaign of the Galactic centre (GC) by the X-ray telescope (XRT) aboard the Swift satellite (Kennea & The Swift/XRT team 2006), carried out in 2006 and 2007.

5.2 Observations and data analysis

The GC was monitored almost daily with the XRT aboard Swift, from 2006 February 24 until 2007 November 2, with exclusion of the epochs from 2006 November 3 till 2007 March 6 (due to Solar constraints) and 2007 August 11 till September 26 (due to a safe-hold event; Gehrels 2007).\(^2\) Each Swift/XRT pointing typically lasted $\sim 1$ ks, although occasionally longer exposures (up to $\sim 13$ ks) were carried out. Most of the data was collected in photon counting (PC) mode, albeit sometimes an unusual high count rate (due to the occurrence of a type-I X-ray burst) induced an automated switch to the windowed timing (WT) mode. We obtained all observations of 2006–2007 GC monitoring campaign from the Swift data archive.

The XRT data were processed with the task xrtpipeline using standard quality cuts and event grades 0–12 in PC mode (0–2 in WT mode).\(^3\) We searched the data for transient X-ray sources by comparing small segments of Swift data, spanning $\sim 5$ ks, with one another. We found a total of seven different X-ray transients with peak luminosities $\gtrsim 10^{34}$ erg s$^{-1}$. The source coordinates and associated uncertainties of the detected transients were found by running the XRT software task xrtcentroid on the data. The results are listed in Table 5.1. A source was considered in quiescence when it was not detected within a data bin of approximately 5 ks by visual inspection. The unabsorbed 2–10 keV flux corresponding to this threshold depends on the assumed spectral model, but is roughly $2 \times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$. This translates into a luminosity of $\sim 1.5 \times 10^{33}$ erg s$^{-1}$ for a distance of 8 kpc.

Figure 5.1 shows two 0.3–10 keV images of the Swift/XRT campaign, which

\(^2\)The campaign continues in 2008, but the new data will be discussed in a separate paper.

\(^3\)See http://heasarc.gsfc.nasa.gov/docs/swift/analysis for standard Swift analysis threads.
5  Swift observations of subluminous X-ray transients located near the Galactic centre

Table 5.1: Swift/XRT positions (J2000) and errors of the active transients.

<table>
<thead>
<tr>
<th>Source name</th>
<th>R.A.</th>
<th>Dec.</th>
<th>Err.</th>
<th>Comments/Association</th>
</tr>
</thead>
<tbody>
<tr>
<td>AX J1745.6–2901</td>
<td>17h45m35.44s</td>
<td>−29°01′33.6″</td>
<td>3.5″</td>
<td>New outburst from known transient Swift J174535.5–290135</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>CXOGC J174535.6–290133</td>
</tr>
<tr>
<td>CXOGC J174535.5–290124</td>
<td>17h45m35.80s</td>
<td>−29°01′21.0″</td>
<td>3.5″</td>
<td>New outburst from known transient 4,5</td>
</tr>
<tr>
<td>CXOGC J174540.0–290005</td>
<td>17h45m40.29s</td>
<td>−29°00′05.4″</td>
<td>3.5″</td>
<td>New outburst from known transient 6,7,8,9</td>
</tr>
<tr>
<td>Swift J174553.7–290347</td>
<td>17h45m53.79s</td>
<td>−29°03′47.8″</td>
<td>3.5″</td>
<td>New transient CXOGC J174553.8–290346? This work, 4</td>
</tr>
<tr>
<td>Swift J174622.1–290634</td>
<td>17h46m22.14s</td>
<td>−29°06′34.7″</td>
<td>3.6″</td>
<td>New transient This work</td>
</tr>
<tr>
<td>GRS 1741–2853</td>
<td>17h45m02.43s</td>
<td>−28°54′50.0″</td>
<td>3.5″</td>
<td>New outburst from known transient 2,10,11,12, 14</td>
</tr>
<tr>
<td>XMM J174457–2850.3</td>
<td>17h44m57.30s</td>
<td>−28°50′20.8″</td>
<td>4.0″</td>
<td>New outburst from known transient 12, 13, 14</td>
</tr>
</tbody>
</table>

Note.– The quoted coordinate errors refer to 90% confidence level and were calculated using the software tool xrtcentroid. References: 1=Kennea et al. (2006a), 2=Porquet et al. (2007), 3=Maeda et al. (1996), 4=Muno et al. (2004), 5=Wijnands et al. (2005c), 6=Kennea et al. (2006c), 7=Kennea et al. (2006b), 8=Wang et al. (2006), 9=Muno et al. (2005b), 10=Muno et al. (2003a), 11=Wijnands et al. (2007), 12=Wijnands et al. (2006a), 13=Sakano et al. (2005), 14=Muno et al. (2007b).

covered a total field of $\sim 26' \times 26'$ of sky around Sgr A* (note that individual pointings have a smaller field of view, FOV). Figure 5.1 displays a merged image of all PC mode observations carried out in 2006 and 2007. Apart from many persistent X-ray sources and strong diffuse emission around Sgr A*, it shows six different X-ray transients with peak luminosities $\gtrsim 10^{34}$ erg s$^{-1}$ (listed in Table 5.1). Figure 5.1 also includes a magnified image of the inner region around Sgr A*, taken from the epoch 2006 June 30 till November 2. This was the only episode during the entire 2006–2007 Swift monitoring campaign in which AX J1745.6–2901 was not active, and a seventh active transient, CXOGC J174535.5–290124, could be detected. CXOGC J174535.5–290124 and AX J1745.6–2901 are so close together, that Swift cannot spatially resolve both sources when the latter, which is the brighter of the two, is active. Apart from CXOGC J174535.5–290124, this image also shows CXOGC
5.2 Observations and data analysis

Figure 5.1: X-ray images (0.3–10 keV) of the GC obtained with Swift/XRT (North is up and East is to the right). Left: Merged image of all PC mode observations carried out in 2006 and 2007. The known X-ray transients AX J1745.6–2901, CXOGC J174540.0–290005, GRS 1741–2853 and XMM J174457–2850.3, as well as the newly discovered subluminous X-ray transients Swift J174553.7–290347 and Swift J174622.1–290634 can be seen in this image. Right: Magnified image of the inner region around Sgr A* of the epoch 2006 June–November, during which CXOGC J174535.5–290124 and CXOGC J174540.0–290005 were both detected in an active state. The Swift/XRT position for AX J1745.6–2901 is also plotted, to show that the active object does not coincide with the coordinates of AX J1745.6–2901 and is in fact a distinct source.

J174540.0–290005, which lies North of Sgr A*.

We extracted source lightcurves and spectra (using XSELECT v. 2.3) from the event lists using a circular region with a radius of 10 or 15 pixels (the largest regions were used for the brightest sources). Spectra were extracted only from the data in which a source was active, whereas lightcurves were constructed from all data where a source was in FOV. Corresponding background lightcurves and spectra were averaged over a set of three nearby source-free regions, each of which had the same shape and size as the source region. For none of the transients it was possible to use an annulus for the background subtraction, either because the objects were too close to the edge of the CCD or using an annular background region would encompass too much contamination from nearby X-ray sources or diffuse emission around Sgr A*. The spectra were grouped using the GTABLE command, to contain bins with a minimum of 20 photons.

Exposure maps were generated with XRTEXPOMAP to correct the spectra for fractional exposure loss due to bad columns on the CCD (Abbey et al. 2006).4 The generated exposure maps were used as input to create ancillary response files (arf) with XRTMKARF. We used the latest versions of the response matrix files (v. 10; rmf) from the CALDB database. For the brightest of the seven transients, AX J1745.6–2901 and GRS 1741–2853, the 2007 PC mode data was affected by pile-up. We attempted

4See also http://www.swift.ac.uk/XRT.shtml.
Swift observations of subluminous X-ray transients located near the Galactic centre

Table 5.2: Chandra positions (J2000) and errors of the active transients.

<table>
<thead>
<tr>
<th>Source name</th>
<th>R.A.</th>
<th>Decl.</th>
<th>Err.</th>
<th>Obs ID</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>AX J1745.6–2901</td>
<td>17h45m35.63s</td>
<td>−29°01′34.0″</td>
<td>0.6″</td>
<td>6639</td>
<td>2006-04-11</td>
</tr>
<tr>
<td>CXOGC J174535.5–290124</td>
<td>17h45m35.56s</td>
<td>−29°01′23.9″</td>
<td>0.6″</td>
<td>6644</td>
<td>2006-08-22</td>
</tr>
<tr>
<td>CXOGC J174540.0–290005</td>
<td>17h45m40.06s</td>
<td>−29°00′05.5″</td>
<td>0.6″</td>
<td>6646</td>
<td>2006-10-29</td>
</tr>
<tr>
<td>Swift J174553.7–290347</td>
<td>17h45m53.94s</td>
<td>−29°03′46.9″</td>
<td>0.6″</td>
<td>6363</td>
<td>2006-07-17</td>
</tr>
<tr>
<td>Swift J174622.1–290634</td>
<td>17h46m22.25s</td>
<td>−29°06′32.5″</td>
<td>1.3″</td>
<td>6642</td>
<td>2006-07-04</td>
</tr>
</tbody>
</table>

Note.– The quoted position uncertainties (1σ) were calculated by taking the square root of the quadric sum of the statistical error (from the wavdetect routine) and the uncertainty in absolute astrometry (0.6″; Aldcroft et al. 2000).

to correct for the consequent effect on spectral shape and loss in source flux by the same methods as described by Vaughan et al. (2006).5

Using Xspec (v. 11; Arnaud 1996), we fitted all grouped spectra with a powerlaw continuum model modified by absorption. From these fits we deduce the 2–10 keV mean unabsorbed outburst flux for each source and combined this with the average 2–10 keV Swift/XRT count rate of the outburst to infer a flux-to-count rate conversion factor. This factor was then used to determine the 2–10 keV unabsorbed peak flux for each source from the maximum count rate observed.

5.2.1 Chandra data

To obtain more accurate position information for the X-ray transients, we searched for Chandra archival data of the time the transients were in outburst. We found several Chandra observations at times when our seven Swift transients were active (see Table 5.2). We analysed these Chandra data using the CIAO tools (v. 4.0) and the standard Chandra analysis threads.6 The Chandra source positions and associated errors were determined using the tool wavdetect and are also listed in Table 5.2.

5.2.2 Time-averaged accretion rates

Assuming that the observed transients are accreting neutron stars or black holes in X-ray binaries, we can estimate the mean accretion rate during an outburst, \( \langle \dot{M}_{\text{obs}} \rangle \), from the mean unabsorbed outburst flux. Following in’t Zand et al. (2007), we apply a correction factor of 3 to the mean 2–10 keV outburst luminosity (unabsorbed, inferred from spectral fitting) to obtain the 0.1–100 keV accretion luminosity \( L_{\text{acc}} \) (which is an approximation of the bolometric luminosity of the source).

5See also http://www.swift.ac.uk/pileup.shtml.
The mass-accretion rate during outburst is then estimated by employing the relation 
\[ \langle \dot{M}_{\text{ob}} \rangle = \frac{R L_{\text{acc}}}{GM} \]
where \( G = 6.67 \times 10^{-8} \text{ cm}^3 \text{ g}^{-1} \text{ s}^{-2} \) is the gravitational constant. We adopt \( M = 1.4 \, M_\odot \) and \( R = 10 \text{ km} \) for a neutron star accretor and \( M = 10 \, M_\odot \) and \( R = 30 \text{ km} \) for the scenario of a black hole primary. Presuming that the observed outburst is typical, we convert the mass-accretion rate during outburst to a long-term averaged value, \( \langle \dot{M}_{\text{long}} \rangle \), by using the relation 
\[ \langle \dot{M}_{\text{long}} \rangle = \langle \dot{M}_{\text{ob}} \rangle \times \frac{t_{\text{ob}}}{t_{\text{rec}}} \]
where \( t_{\text{ob}} \) is the outburst duration and \( t_{\text{rec}} \) is the system’s recurrence time, i.e., the sum of the outburst and quiescence time scales. The factor \( \frac{t_{\text{ob}}}{t_{\text{rec}}} \) represents the duty cycle of the system.

The calculation of the time-averaged accretion rate, as described above, is subject to several uncertainties. Both the translation from the observed 2–10 keV luminosity to the bolometric luminosity, as well as the conversion to the mass-accretion rate are uncertain (the exact efficiency of converting gravitational potential energy to X-ray radiation is unknown). Furthermore, many X-ray transients show irregular outburst- and recurrence times, which makes it difficult to estimate their duty cycles and what we observe over the course of a few years may not be typical for their long-term accretion history. However, the quasi-daily Swift monitoring observations of 2006–2007 provide an unique insight in the outburst behaviour of these subluminous transients, allowing for a better estimate of their duty cycles than would be possible based on single, randomly spaced pointings alone. With the method described above, we can at least get an order of magnitude estimate of their time-averaged accretion rates.

An important caveat is that accretion flows around low luminosity (below a few percent of Eddington) black holes might be radiative inefficient (e.g., Blandford & Begelman 1999; Narayan & McClintock 2008). If this is the case, the mass-accretion rate as inferred from the X-ray luminosity can be severely underestimated. Thus, in particular the values inferred for the black hole scenario should be considered with caution (see Section 5.4.5).

### 5.3 X-ray lightcurves and spectra

The background corrected lightcurves of the seven transients are displayed in Figure 5.2 and their spectra are plotted in Figure 5.3. The X-ray properties of each individual source will be discussed below; a summary of the spectral parameters for all sources can be found in Table 5.3. All detected transients were heavily absorbed \( (N_H \gtrsim 6 \times 10^{22} \text{ cm}^{-2}) \), consistent with what is observed for sources close to Sgr A*. Therefore, throughout this paper we assume a distance of 8 kpc for all detected transients when calculating their 2–10 keV X-ray luminosities.
5 Swift observations of subluminous X-ray transients located near the Galactic centre

Figure 5.2: Background-corrected Swift/XRT lightcurves of the transients that were active during the Swift monitoring campaign of the GC in 2006 and 2007. During days 252–374 after the start of the survey (2006 February 24), no observations were carried out due to Solar constraints. In between days 533–579, all Swift’s instruments were off-line due to a safe-hold event (Gehrels 2007). We could only deduce information on the activity of CXOGC J174535.5–290124 from Swift observations at times that the nearby, brighter transient AX J1745.6–2901 was not active. This was the case from 2006 late-June till early- November, so the lightcurve of CXOGC J174535.5–290124 only covers this epoch.
Figure 5.2: Continued. – Swift J174622.1–290634, GRS 1741–2853 and XMM J174457–2850.3 were not always in FOV of the observations, so lightcurves of these three sources contain more data gaps than that of the other transients. The plot of GRS 1741–2853 includes a zoom in of a small outburst that occurred in 2006.
Figure 5.3: *Swift*/XRT background-corrected spectra of the seven X-ray transients that were found to be active during the *Swift* monitoring campaign of the field around Sgr A* in 2006 and 2007. The absorbed powerlaw model fit is plotted along with the data points for each source. For AX J1745.6–2901 three different spectra are shown: the average outburst spectrum of 2007 (upper), 2006 (middle) and the quiescent spectrum (lower) observed by Muno et al. (2004). For the calculation of the average 2006 spectrum, we removed the two observations in which type-I X-ray bursts were detected. The plot of Swift J174553.7–290347 includes the X-ray spectrum of CXOGC J174553.8–290346 (from Muno et al. 2004), which possibly represents the quiescent state of this transient. GRS 1741–2853 displayed separate outbursts in 2006 and 2007; average spectra of both outbursts are shown.
Table 5.3: Results from spectral data analysis.

<table>
<thead>
<tr>
<th>Source name</th>
<th>Year</th>
<th>$N_{\text{H}}$</th>
<th>$\Gamma$</th>
<th>$\chi^2$</th>
<th>$F_{\text{abs}}^X$</th>
<th>$F_{\text{abs}}^\nu$</th>
<th>$F_{\text{abs}}^X$</th>
<th>$L_X$</th>
<th>$L_X^{\text{peak}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>AX J1745.6–2901</td>
<td>2006</td>
<td>23.1 ± 1.3</td>
<td>2.3 ± 0.2</td>
<td>1.11</td>
<td>14.7 ± 0.3</td>
<td>50.4 ± 4.2</td>
<td>120</td>
<td>39</td>
<td>92</td>
</tr>
<tr>
<td></td>
<td>2007</td>
<td>24.9 ± 0.7</td>
<td>2.8 ± 0.1</td>
<td>1.14</td>
<td>44.8 ± 0.4</td>
<td>205 ± 10</td>
<td>800</td>
<td>160</td>
<td>610</td>
</tr>
<tr>
<td>CXOGC J174535.5–290124</td>
<td>2006</td>
<td>14.2 ± 6.3</td>
<td>1.1 ± 1.2</td>
<td>1.40</td>
<td>1.25 ± 0.23</td>
<td>2.25 ± 0.76</td>
<td>4.0</td>
<td>1.7</td>
<td>3.0</td>
</tr>
<tr>
<td>CXOGC J174540.0–290005</td>
<td>2006</td>
<td>8.63 ± 5.33</td>
<td>1.4 ± 1.0</td>
<td>1.54</td>
<td>7.81 ± 0.90</td>
<td>12.5 ± 3.6</td>
<td>30</td>
<td>9.6</td>
<td>23</td>
</tr>
<tr>
<td>Swift J174553.7–290347</td>
<td>2006</td>
<td>24.4 ± 8.9</td>
<td>3.0 ± 1.4</td>
<td>1.23</td>
<td>1.53 ± 0.23</td>
<td>7.73 ± 2.65</td>
<td>26</td>
<td>5.9</td>
<td>20</td>
</tr>
<tr>
<td>Swift J174622.1–290634</td>
<td>2006</td>
<td>11.7 ± 5.0</td>
<td>3.3 ± 1.2</td>
<td>0.57</td>
<td>0.468 ± 0.064</td>
<td>1.55 ± 1.31</td>
<td>9.1</td>
<td>1.2</td>
<td>7.0</td>
</tr>
<tr>
<td>GRS 1741–2853</td>
<td>2006</td>
<td>14 fix</td>
<td>5.0 ± 2.6</td>
<td>0.84</td>
<td>0.646 ± 0.312</td>
<td>5.07 ± 3.37</td>
<td>12</td>
<td>3.9</td>
<td>9.2</td>
</tr>
<tr>
<td></td>
<td>2007</td>
<td>14.0 ± 1.0</td>
<td>2.6 ± 0.2</td>
<td>1.15</td>
<td>61.6 ± 1.2</td>
<td>175 ± 16</td>
<td>260</td>
<td>130</td>
<td>200</td>
</tr>
<tr>
<td>XMM J174457–2850.3</td>
<td>2007</td>
<td>6 fix</td>
<td>1.3 fix</td>
<td>0.21</td>
<td>0.29</td>
<td>1.4</td>
<td>0.22</td>
<td>1.1</td>
<td></td>
</tr>
</tbody>
</table>

Note.– All quoted fluxes are for the 2–10 keV band and given in units of $10^{-12}$ erg cm$^{-2}$ s$^{-1}$. The X-ray luminosities, given in units of $10^{34}$ erg s$^{-1}$, are calculated from the unabsorbed 2–10 keV fluxes assuming a distance of 8 kpc for all sources. The fluxes and luminosities of XMM J174457–2850.3 were deduced using rmmms, with $N_{\text{H}}$ and $\Gamma$ fixed at the values obtained by Sakano et al. (2005). The hydrogen column density is given in units of $10^{22}$ cm$^{-2}$.

5.3.1 AX J1745.6–2901

The start of the Swift/GC monitoring observations in 2006 immediately revealed the new X-ray transient Swift J174535.5–290135, which is located ∼ 1.5′ SE from Sgr A* (Kennea et al. 2006a). This X-ray source remained active for approximately 16 weeks until it returned to quiescence in 2006 late-June. Renewed activity of the system was reported in 2007 February (Wijnands et al. 2007; Kuulkers et al. 2007a), and the Swift/GC monitoring observations suggest that it remained as such for more than a year, as it was active until the campaign ended in 2007 November (see Figure 5.2). We note that the monitoring campaign continued in 2008 and that the source was detected throughout 2008. However, a detailed discussion of those observations are beyond the scope of our paper. The detection of eclipses with an 8.4-h period seen in XMM-Newton observations (Porquet et al. 2007), positively identify Swift J174535.5–290135 with the ASCA detected eclipsing X-ray burster AX J1745.6–
Swift observations of subluminous X-ray transients located near the Galactic centre

2901 (Maeda et al. 1996). In addition, the Chandra position of AX J1745.6–2901 (see Table 5.2) is consistent with that of the X-ray source CXOGC J174535.6–290133 (Muno et al. 2003b), which likely represents the quiescent counterpart of the system.

Figure 5.2 displays the activity of AX J1745.6–2901 during the 2006–2007 Swift campaign. In 2006, the outburst reached a peak luminosity of $9.2 \times 10^{35}$ erg s$^{-1}$, while the average outburst luminosity was $3.9 \times 10^{35}$ erg s$^{-1}$ (both in the 2–10 keV energy band). For an outburst duration of at least 16 weeks (AX J1745.6–2901 might have been active before the start of the Swift monitoring campaign), we can deduce a fluence of $\gtrsim 1.8 \times 10^{-4}$ erg cm$^{-2}$ s$^{-1}$. In 2007, the system was active again, but with an higher average luminosity of $1.6 \times 10^{36}$ erg s$^{-1}$ and a reached peak value of $6.1 \times 10^{36}$ erg s$^{-1}$ (both 2–10 keV). Different outburst luminosities have been reported for AX J1745.6–2901 in the past; in 1993 October the source was detected at a luminosity of $2 \times 10^{35}$ erg s$^{-1}$, while in 1994 October it became as bright as $9 \times 10^{35}$ erg s$^{-1}$ (both values are in the 3–10 keV band, Maeda et al. 1996).

Before and after the 6-week epoch in 2007 that the Swift observatory was offline due to a safe-hold event (Gehrels 2007, this corresponds to days 533-579 in the lightcurves displayed in Figure 5.2), AX J1745.6–2901 was active at similar count rates. We have inspected proprietary XMM-Newton data of the GC performed on 2007 September 6 (see Chapter 7), i.e., halfway the interval that the Swift observatory was offline. AX J1745.6–2901 was clearly detected during that observation, which demonstrates that the source remained active all through the 2007 Swift monitoring campaign. For an outburst duration of 34 weeks, the 2–10 keV fluence of the 2007 outburst is then $5.7 \times 10^{-3}$ erg cm$^{-2}$. However, this inferred value should be considered a lower limit, since we also found AX J1745.6–2901 to be active during all Swift/GC monitoring observations in 2008, at a flux similar to that of 2007 (the source was also reported active during Chandra observations carried out in 2008, see Heinke et al. (2008) and Degenaar et al. (2008a)). This suggests that the outburst observed in 2007, continued in 2008 and thus has a duration of at least 1.5 years. For that outburst length, the fluence increases to $6.5 \times 10^{-3}$ erg cm$^{-2}$ (2–10 keV), and will become even larger if the outburst continues.

Between 1999 and 2002, the GC was observed several times with Chandra (Muno et al. 2003b, 2004). Thus, if the observed long outburst duration of AX J1745.6–2901 is typical, the source likely resided in quiescence for at least 4 years. However, the quiescent time scale must be less than 13 years, the time since the ASCA discovery (Maeda et al. 1996). Estimating the long-term time-averaged mass-accretion rate for AX J1745.6–2901 is difficult due to the different outburst durations and luminosities the system displays. To get a rough estimate, we will assume that an outburst duration of 1.5 years and a 2–10 keV outburst luminosity of $2 \times 10^{36}$ erg s$^{-1}$ are typical for the source. The duty cycle of this neutron star system then ranges from 10% for
$t_q \sim 13$ yr up to 30% for $t_{rec} \sim 4$ yr. This results in an estimated long-term time-averaged accretion rate of $\sim (5 - 15) \times 10^{-11}$ $M_\odot$ yr$^{-1}$ (see Table 5.4). This value might be a lower limit, since AX J1745.6–2901 possibly exhibited more outbursts like the smaller one observed in 2006. On the other hand, the observed long outburst of 1.5 years might not be typical for the system, in which case this estimate would be an upper limit on the time-averaged mass-accretion rate.

To compare the outburst spectrum of AX J1745.6–2901 with the likely quiescent counterpart of the source (CXOGC J174535.6–290133), we downloaded the reduced data of the Chandra monitoring campaign that are made available online. After the spectrum was grouped to contain at least 20 photons per bin, we fitted it with an absorbed powerlaw model with the hydrogen column density fixed at the 2006 outburst value ($N_H = 23.1 \times 10^{22}$ cm$^{-2}$). This resulted in a powerlaw index of $\Gamma = 1.8 \pm 0.5$ and an unabsorbed 2–10 keV flux of $(7.7 \pm 0.4) \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$. The inferred 2–10 keV luminosity is $5.9 \times 10^{32}$ erg s$^{-1}$. The quiescent spectrum is plotted in Figure 5.3 along with the average outburst spectra of 2006 and 2007.

### Type-I X-ray bursts

The Swift/GC monitoring observations detected two type-I X-ray bursts from AX J1745.6–2901. The times at which these bursts occurred are indicated in Figure 5.2. The first burst was observed on 2006 June 3 and had an exponential decay time scale of $\sim 10$ s (see Figure 5.4). Due to the sudden increase in count rate associated with the X-ray burst, the XRT instrument automatically switched from PC to WT mode. There is no burst data available during this switch, which took about 3 s. We extracted the spectrum of the first 3 s of the observed burst peak and fitted it to an absorbed blackbody model with the hydrogen column density fixed at $N_H = 23.1 \times 10^{22}$ cm$^{-2}$, the value inferred from the mean outburst spectrum of 2006. This yielded $kT = 1.7_{-0.6}^{+1.9}$ keV and a radiating surface area of $10^{+12}_{-6}$ km (assuming $D = 8$ kpc). The 0.01–100 keV peak flux inferred from our spectral fit is $1.3_{-0.1}^{+2.1} \times 10^{-8}$ erg cm$^{-2}$ s$^{-1}$ (corrected for absorption), which translates into an observed peak luminosity of $9.6 \times 10^{37}$ erg s$^{-1}$. However, the true burst peak was likely missed due to the automatic switch of XRT modes. If we extrapolate the burst lightcurve to the time $t = -3$ s (i.e., the time of the mode-switch), we can deduce a 0.01–100 keV peak luminosity of $1.3 \times 10^{38}$ erg s$^{-1}$. Although the true peak of the type-I X-ray bursts will remain uncertain, it is clear that it likely was close to the Eddington luminosity for a neutron star ($2.0 \times 10^{38}$ erg s$^{-1}$ for a hydrogen-rich and $3.8 \times 10^{38}$ erg s$^{-1}$ for a hydrogen-poor photosphere; e.g., Kuulkers et al. 2003).

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Another burst was observed on 2006 June 14, which had an exponential decay time scale of $\sim 20$ s (see Figure 5.4). This time, no automated switch of XRT modes occurred, so that the burst was fully detected in the PC mode. Due to the high count rate associated with the burst, the PC image was severely piled-up and a proper spectral fitting of the burst peak was not possible. Therefore, we used the burst count rate to find the peak flux and luminosity. To obtain the correct count rates, the observed ones have to be corrected for the loss in photons caused by bad columns and pixels using an exposure map, and a pile-up correction needs to be applied. For the latter, we extracted the source photons from an annular source region, avoiding the piled-up inner pixels. We determined the proper correction factor for the observed PC count rate following analysis threads on the Swift webpages. This way, we found that the burst must have reached a peak count rate of 15 cnts s$^{-1}$ in the PC mode. Employing RMMS with a hydrogen column density of $N_H = 23.1 \times 10^{22}$ cm$^{-2}$ (the 2006 outburst value) and temperatures of $kT = 1.0 – 3.0$ keV (roughly the range inferred for the first burst), we can estimate an unabsorbed 0.01–100 keV flux of $(0.68 – 1.0) \times 10^{-8}$ erg cm$^{-2}$ s$^{-1}$. The corresponding 0.01–100 keV peak luminosity is $(0.52 – 1.1) \times 10^{38}$ erg s$^{-1}$, i.e., comparable to the X-ray burst that occurred on 2006 June 3.
5.3 X-ray lightcurves and spectra

5.3.2 CXOGC J174535.5–290124

By the beginning of 2006 August, a transient was detected in outburst approximately 1.3′ SE from Sgr A∗. The XRT position for this source, which is listed in Table 5.1, is only ∼14″ away from the above discussed AX J1745.6–2901, which had returned to quiescence a month earlier. We obtained an improved position for this transient from an archival Chandra observation performed on 2006 August 22 (see Table 5.2) and find that its coordinates are not consistent with the Chandra position of AX J1745.6–2901 (Table 5.2), but do coincide with that of the known X-ray transient CXOGC J174535.5–290124 (Muno et al. 2005b).

CXOGC J174535.5–290124 is a subluminous X-ray transient that was discovered during a Chandra campaign of the GC (Muno et al. 2004). Whereas the source was not detected in 1999 and 2000 (yielding a 2–8 keV upper limit for the quiescent luminosity of $L_X < 9 \times 10^{30}$ erg s$^{-1}$; Muno et al. 2005b), it was found in outburst with Chandra on several occasions between 2001 and 2005, displaying typical 2–8 keV luminosities of $10^{33–34}$ erg s$^{-1}$ (Muno et al. 2005b; Wijnands et al. 2005c; Degenaar et al. 2008a). The source was also detected in outburst during XMM-Newton observations obtained in September 2006, when it displayed a 2–10 keV X-ray luminosity of $2 \times 10^{34}$ erg s$^{-1}$ (Wijnands et al. 2006b). This is in agreement with the 2006 Swift data of CXOGC J174535.5–290124 (see Table 5.3), which showed an average outburst luminosity of $1.7 \times 10^{34}$ erg s$^{-1}$ and an observed peak luminosity of $3.0 \times 10^{34}$ erg s$^{-1}$ (both in the 2–10 keV energy band). The source was observed in outburst until the Swift observations stopped in November 2006. The outburst of late 2006 thus had a duration of at least 12 weeks. This yields a lower limit on the outburst fluence of $1.6 \times 10^{-5}$ erg cm$^{-2}$ s$^{-1}$ in the 2–10 keV energy band.

The nearby transient AX J1745.6–2901 is typically a factor 10–100 brighter during outburst than CXOGC J174535.5–290124, and due to their small separation, we cannot deduce any information on CXOGC J174535.5–290124 from Swift data when AX J1745.6–2901 is active. However, Chandra does have the required spatial resolution to separate these two transients, even when AX J1745.6–2901 is in outburst. Inspection of archival Chandra data of both 2006 and 2007 revealed that CXOGC J174535.5–290124 was in outburst simultaneously with AX J1745.6–2901 in 2006 April (Obs ID 6639), although it was not active during Chandra observations carried out in 2006 May, June and early-July. Thus, CXOGC J174535.5–290124 must have returned to quiescence by the end of 2006 April, but it reappeared in 2006 August, when Swift detected the source. Since AX J1745.6–2901 was continuously active during the Swift/GC monitoring observations of 2007, we cannot deduce any information on the activity CXOGC J174535.5–290124 from the 2007 Swift data. However, the source is found active Chandra data obtained in 2007 March, April and May (Degenaar et al. in prep.; see Chapter 7). In 2008, CXOGC J174535.5–290124 is re-
ported active during pointed Chandra/HRC-I observations performed on May 10-11 (Degenaar et al. 2008a). During that observation the 2–10 keV X-ray luminosity was approximately $2 \times 10^{33}$ erg s$^{-1}$, i.e., a factor of 10 below the outburst level detected with Swift in 2006.

Despite its low peak luminosity, CXOGC J174535.5–290124 appears to be active quite regularly. However, its duty cycle is not completely clear; the Swift observations show that in 2006 the system was in quiescence for about 3 months in between two outbursts. Tentatively assuming a recurrence time of 3–12 months and a typical outburst duration of 12 weeks, the duty cycle for CXOGC J174535.5–290124 is $\sim 20$ – 50%. The various detections of CXOGC J174535.5–290124 vary between a few times $10^{33}$–$10^{34}$ erg s$^{-1}$, so we adopt a mean 2–10 keV outburst luminosity of $1 \times 10^{34}$ erg s$^{-1}$. This results in a long-term averaged accretion rate of $5 \times 10^{-13} \ M_\odot$ yr$^{-1} \lesssim \langle \dot{M}_{\text{long}} \rangle \lesssim 1 \times 10^{-12} \ M_\odot$ yr$^{-1}$ for a neutron star primary or $7 \times 10^{-14} \ M_\odot$ yr$^{-1} \lesssim \langle \dot{M}_{\text{long}} \rangle \lesssim 2 \times 10^{-13} \ M_\odot$ yr$^{-1}$ in case of a black hole accretor (see Table 5.4).

### 5.3.3 CXOGC J174540.0–290005

In 2006 late-October Kennea et al. (2006c) reported on activity from an X-ray transient, Swift J174540.2–290005, located $\sim 20''$ N from Sgr A*. In an archival Chandra observation performed on 2006 August 22, we find one X-ray source within the XRT error radius of Swift J174540.2–290005 (see Table 5.1). The Chandra position of this source (see Table 5.2) is consistent with that of CXOGC J174540.0–290005 (Muno et al. 2005b), positively identifying Swift J174540.2–290005 with this Chandra-discovered X-ray transient. CXOGC J174540.0–290005 was detected in outburst only once before, in 2003, when it displayed a luminosity of $3.4 \times 10^{34}$ erg s$^{-1}$ (2–8 keV, Muno et al. 2005b). This is a factor of a few lower than the peak luminosity of $2.3 \times 10^{35}$ erg s$^{-1}$ that was detected by Swift in 2006 (2–10 keV, see Table 5.3). Muno et al. (2005b) derived an upper limit for the quiescent luminosity of this system of $< 4 \times 10^{34}$ erg s$^{-1}$ (2–8 keV).

The 2006 outburst of CXOGC J174540.0–290005 lasted almost 2 weeks, and the inferred outburst fluence is $1.3 \times 10^{-5}$ erg cm$^{-2}$ (2–10 keV). No other outburst from CXOGC J174540.0–290005 was detected during the Swift observing campaign of 2006 and 2007. If the observed outburst duration of 2 weeks is typical for this source, than its outbursts are most easily missed. However, CXOGC J174540.0–290005 was in FOV during the entire Swift campaign of 2006, which encompassed almost daily observations and lasted for 35 weeks. No activity from the source was detected in 33 weeks prior to the outburst that occurred in late October. Therefore, we can assume an upper limit on the duty cycle of $\lesssim 6\%$. This is consistent with the fact that no outburst was detected during the 2007 Swift monitoring observations.
However, since the source was detected with Chandra in 2003 (Muno et al. 2005b), we can also assume that the recurrence time of the system is less than 3 years. From this we can deduce that the duty cycle is likely more than 1%. Using these two bounds combined with an averaged 2–10 keV outburst luminosity of $1 \times 10^{35}$ erg s$^{-1}$, we can put a limit on the time-averaged mass-accretion rate of $3 \times 10^{-13} \, M_\odot \, \text{yr}^{-1} \leq \langle M_{\text{long}} \rangle \leq 1.5 \times 10^{-12} \, M_\odot \, \text{yr}^{-1}$ for a neutron star compact primary, or $4 \times 10^{-14} \, M_\odot \, \text{yr}^{-1} \leq \langle M_{\text{long}} \rangle \leq 2.1 \times 10^{-13} \, M_\odot \, \text{yr}^{-1}$ in case it is a black hole.

Following the reported activity of Swift J174540.2–290005 (Kennea et al. 2006c), Wang et al. (2006) performed infrared (IR) observations of the source field on October 30-31, 2006. Whereas no sources within the XRT source position uncertainty showed an expected increase in IR brightness (e.g., Clark et al. 2000; Russell et al. 2006), Wang et al. (2006) concluded that none of them was the counterpart to CXOGC J174540.0–290005. However, we note that the Swift/XRT data shows that at the time of the reported IR observations, the X-ray outburst had already ceased and any correlated IR luminosity might have returned to its pre-outburst level accordingly.

### 5.3.4 Swift J174553.7–290347

A fourth X-ray transient, which we designate Swift J174553.7–290347, is located $\sim 4.5'$ SW from Sgr A* and was found active for a duration of approximately 2 weeks in 2006 June (see Figure 5.2). The source reached a peak luminosity of $2.0 \times 10^{35}$ erg s$^{-1}$, while the average outburst luminosity was $4.9 \times 10^{34}$ erg s$^{-1}$ (both 2–10 keV). We were able to obtain an improved position of Swift J174553.7–290347 from an archival Chandra observation carried out on 2006 June 17 (see Table 5.2). The source coordinates suggests a possible association with the Chandra detected X-ray point source CXOGC J174553.8–290346 (Muno et al. 2003b), although the offset between the source positions is $\sim 1''$. During the Chandra campaign of the GC (Muno et al. 2003b, 2004, 2005b), CXOGC J174553.8–290346 was detected as a low luminosity X-ray source ($L_X \sim 10^{32}$ erg s$^{-1}$, 2–8 keV) that showed no signs of long- or short-term variability (Muno et al. 2003b).

The spectral shape of CXOGC J174553.8–290346 is not reported in literature, but the reduced Chandra data (both source and background spectra as well as proper response files) from the campaign are made available online (see footnote 7 on page 85). For comparison with the current outburst data, we downloaded the reduced Chandra data and fitted the background corrected spectrum with an absorbed power-law model (after the spectra were grouped to contain at least 20 photons per bin). With the absorption column density fixed at the outburst value of Swift J174553.7–290347, $N_H = 24.4 \times 10^{22}$ cm$^{-2}$, this results in a fit with an unusual steep spectrum; $\Gamma = 5.5 \pm 2.0$. The 2–10 keV unabsorbed X-ray flux for this fit is $(5.0 \pm 4.8) \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$ and the associated X-ray luminosity would be $3.8 \times 10^{32}$ erg s$^{-1}$. 

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Leaving the hydrogen column density as a free parameter results in a fit with $N_H = (11.6 \pm 10.1) \times 10^{22} \text{ cm}^{-2}$ and $\Gamma = 3.1 \pm 1.7$ and an X-ray luminosity of $\sim 6.8 \times 10^{31} \text{ erg s}^{-1}$ (2–10 keV). Both the *Swift* outburst spectrum of Swift J174553.7–290347 and the *Chandra* spectrum of CXOGC J174553.8–290346 are plotted in combination with the fitted models in Figure 5.3 (the plotted spectral model for CXOGC J174553.8–290346 is for $N_H = 24.4 \times 10^{22} \text{ cm}^{-2}$).

During the entire 2006–2007 *Swift* campaign, the new X-ray transient Swift J174553.7–290347 only displayed this 2-week outburst (see Figure 5.2), for which we can infer a 2–10 keV outburst fluence of $8.0 \times 10^{-6} \text{ erg cm}^{-2}$. The source was not detected during 22 weeks of consecutive observations in 2007, which we can use as a lower limit on the quiescent time scale of this source (which is consistent with the 2006 behaviour). Thus, the duty cycle of Swift J174553.7–290347 is likely less than 8%. The estimate for the long-term average accretion rate of this transient is then $\lesssim 10^{-12} \text{ M}_\odot \text{ yr}^{-1}$ for a neutron star X-ray binary or $\lesssim 2 \times 10^{-13} \text{ M}_\odot \text{ yr}^{-1}$ in case of an accreting black hole.

### 5.3.5 Swift J174622.1–290634

Approximately 11′ SW from Sgr A*, the X-ray transient Swift J174622.1–290634 is active from 2006 mid-May till late-June (see Figure 5.2). We obtained improved coordinates for this new X-ray transient from an archival *Chandra* observation carried out on 2006 July 7, during which the source was detected (see Table 5.2). This system cannot be identified with any known X-ray source (it was outside FOV of the *Chandra* monitoring campaign of the GC; Muno et al. 2003b, 2004, 2005b). The average outburst luminosity during the *Swift*/XRT observations was $1.2 \times 10^{34} \text{ erg s}^{-1}$ and the observed peak luminosity was $7.0 \times 10^{34} \text{ erg s}^{-1}$ (both in the 2–10 keV energy band). The 2–10 keV outburst fluence for the 5-week outburst of Swift J174622.1–290634 is $5.0 \times 10^{-6} \text{ erg cm}^{-2}$.

Swift J174622.1–290634 lies relatively far from Sgr A* and was not always within the FOV, due to varying pointing centres and roll-angles of the *Swift*/XRT observations. However, the observations were spread such that if the observed outburst duration of 5 weeks is typical for the source, any other outburst occurring during the 2006 monitoring campaign would have been detected by *Swift*/XRT. During the 6-week interval that the *Swift* observatory was offline in 2007, Swift J174622.1–290634 could in principle have experienced an accretion outburst of 5 weeks. However, the system was not detected during *XMM-Newton* observations of the GC performed on 2007 September 6 (i.e., halfway the interval that the *Swift* observatory was offline), indicating that this is not the case. We therefore assume that the source was in quiescence for the entire 2007 *Swift* monitoring campaign, which lasted for 31 weeks. The duty cycle of Swift J174622.1–290634 is thus likely less than 14%, which makes...
its time-averaged accretion rate \( \lesssim 4 \times 10^{-13} \, M_\odot \, \text{yr}^{-1} \) for an accreting neutron star or 
\( \lesssim 6 \times 10^{-14} \, M_\odot \, \text{yr}^{-1} \) for a black hole X-ray binary.

5.3.6 GRS 1741–2853

The neutron star X-ray transient GRS 1741–2853 (located \( \sim 10' \) NE from Sgr A*) was in FOV during most of the Swift monitoring observations (see Figure 5.2). The source has been detected in an active state several times since its initial discovery in 1990 (Sunyaev 1990), displaying typical peak luminosities of a few times \( 10^{36} \, \text{erg s}^{-1} \) (e.g., Muno et al. 2003a; Wijnands et al. 2006a). In 2006 September, GRS 1741–2853 displayed some low level activity, lasting approximately a week (see Figure 5.2, \( \sim 200 \) days after the start of the monitoring observations). The source reached a peak luminosity of \( 8.9 \times 10^{34} \, \text{erg s}^{-1} (2–10 \, \text{keV}) \), which is an order of magnitude lower than its full outburst luminosity, but still about 1000 times higher than its quiescent level (\( \sim 10^{32} \, \text{erg s}^{-1} \) in the 2–8 keV band; Muno et al. 2003a). The fluence of this small outburst is \( 2.6 \times 10^{-6} \, \text{erg cm}^{-2} \) (2–10 keV).

Renewed activity from GRS 1741–2853 was reported in early 2007, as observed with Integral (Kuulkers et al. 2007b), Swift (Wijnands et al. 2007), XMM-Newton (Porquet et al. 2007) and Chandra (Muno et al. 2007b). During its 2007 activity, three type-I X-ray bursts were reported (Wijnands et al. 2007; Porquet et al. 2007) and several of such thermonuclear bursts have been observed in the past (see Muno et al. 2003a, and references therein). GRS 1741–2853 was seen active right from the start of the 2007 Swift/GC observation performed on March 3. It remained as such for approximately 5 weeks, displaying an average 2–10 keV outburst luminosity of \( 1.3 \times 10^{36} \, \text{erg s}^{-1} \), until it returned to quiescence by the beginning of April. During this outburst, Swift/XRT detected a peak luminosity of \( 2.0 \times 10^{36} \, \text{erg s}^{-1} \) (2–10 keV). For the observed outburst duration of 5 weeks, the 2–10 keV fluence of the 2007 outburst is \( 5.3 \times 10^{-6} \, \text{erg cm}^{-2} \).

However, GRS 1741–2853 was already seen active during Integral observations performed on February 15, i.e., 2 weeks before the start of the Swift/GC campaign. Moreover, Wijnands et al. (2007) noted that GRS 1741–2853 is located within the 3' error circle of an X-ray burst detected by the Burst Alert Telescope (BAT) on-board Swift on 2007 January 22 (Fox et al. 2007). As there were no other sources detected within the BAT error circle, it is likely that GRS 1741–2853 was the origin of this burst, suggesting that the source was already active for over 8 weeks before the start of the Swift/GC campaign. Therefore, the outburst fluence inferred from the Swift/XRT observations should be considered as a lower limit and the true value might be \( > 1.4 \times 10^{-3} \, \text{erg cm}^{-2} \) (2–10 keV), in case the outburst lasted 13 weeks, or longer.
Small outbursts like the one occurring in 2006 with $L_{\text{peak}}^X \sim 10^{35}$ erg s$^{-1}$ and $t_{\text{obs}} = 1$ week, have a negligible effect on the total mass-accretion rate, when compared to longer and brighter outbursts like the one observed in 2007. Therefore, we will not include the 2006 outburst in calculating the mass-accretion rate for GRS 1741–2853 and assume a minimal quiescent time scale of 35 weeks (the span of the 2006 monitoring observations). Adapting a typical outburst duration of 13 weeks (which is likely the minimum duration of the 2007 outburst), we can then place an upper limit on the duty cycle of GRS 1741–2853 of $\lesssim 30\%$. On the other hand, GRS 1741–2853 has been detected at 2–10 keV X-ray luminosities of $\sim 10^{36}$ erg s$^{-1}$ for a total of 5 times since its initial discovery 18 years ago (see Wijnands et al. 2006a, for the long-term lightcurve of this source, showing its various outbursts from 1990 till 2005). Therefore, we assume a lower limit on the duty cycle of $\gtrsim 7\%$. Combining these bounds with a typical 2–10 keV outburst luminosity of $\sim 10^{36}$ erg s$^{-1}$, we estimate a long-term accretion rate of $2 \times 10^{-11}$ M$_{\odot}$ yr$^{-1} \lesssim \langle \dot{M}_{\text{long}} \rangle \lesssim 8 \times 10^{-11}$ M$_{\odot}$ yr$^{-1}$ for GRS 1741–2853.

### 5.3.7 XMM J174457–2850.3

XMM J174457–2850.3 is an X-ray transient located about 13.7′ NE from Sgr A*. The source was discovered in 2001 (Sakano et al. 2005), using XMM-Newton observations, at a peak luminosity of $5 \times 10^{34}$ erg s$^{-1}$, but with a quiescent luminosity of $1.2 \times 10^{32}$ erg s$^{-1}$ (both in the 2–10 keV energy range). Since then, the source has been repeatedly reported active at luminosities ranging from a few times $10^{33}$ erg s$^{-1}$ up to $\sim 10^{36}$ erg s$^{-1}$ (Wijnands et al. 2006a; Muno et al. 2007b).

Due to its large angular separation from Sgr A*, there were only 16 pointings (spaced between 2007 July and November) during the Swift/GC campaign, in which XMM J174457–2850.3 was in FOV (see Figure 5.2). Restricted by a small number of photons, we could not fit to the spectrum of XMM J174457–2850.3. We therefore employed $\text{rmm}$s to convert the observed XRT count rates to fluxes using an absorbed powerlaw model with $N_H = 6.0 \times 10^{22}$ cm$^{-2}$ and $\Gamma = 1.3$ (as found by Sakano et al. 2005). During the first set of 6 observations (performed between 2007 July 5–14 for a total of 6 ks), the source had a 2–10 keV X-ray luminosity of $\sim 1.5 \times 10^{33}$ erg s$^{-1}$. This is at a similar level as was found for the source in 2007 February by Muno et al. (2007b). However, on August 4, the source was clearly detected during a single 1.7 ks observation at $L_X \sim 1.1 \times 10^{34}$ erg s$^{-1}$ (2–10 keV). XMM J174457–2850.3 was again in FOV during a series of 6 Swift monitoring observations carried out between 2007 October 24 and November 2 (which had a total exposure time of $\sim 11.1$ ks). At this time, the source activity was lower again; it displayed a 2–10 keV luminosity of $\sim 1.4 \times 10^{33}$ erg s$^{-1}$.

It is possible that XMM J174457–2850.3 did not reach a luminosity exceeding


5.4 Discussion

We have presented the spectral analysis of seven X-ray transients that were found to be active during a monitoring campaign of the field around Sgr A* using Swift/XRT, carried out in 2006–2007. Two new transients were discovered (Swift J174622.1–290634 and Swift J174553.7–290347) and renewed activity from five known sources was observed (AX J1745.6–2901, CXOGC J174535.5–290124, CXOGC J174540.0–290005, GRS 1741–2853 and XMM J174457–2850.3). Adopting source distances of 8 kpc, we can infer peak luminosities in the range of $\sim 1 \times 10^{34} \text{ erg s}^{-1}$ to $6 \times 10^{36} \text{ erg s}^{-1}$ in the 2–10 keV energy band. The two transients AX J1745.6–2901 and GRS 1741–2853 are hybrid systems, that display very-faint outbursts with 2–10 keV peak luminosities of $L_X < 10^{36} \text{ erg s}^{-1}$, as well as outbursts with luminosities in the range of $10^{36}$–$37 \text{ erg s}^{-1}$, which are classified as faint. The other five systems display 2–10 keV peak luminosities of $10^{34}$–$36 \text{ erg s}^{-1}$, i.e., in the very-faint regime. We have observed a large variation in spectral properties, outburst luminosities and outburst durations (see Tables 5.3 and 5.4). In that respect, the subluminous transients are not different from the well-known bright systems.

$\sim 10^{34} \text{ erg s}^{-1}$ during the above described episode. Nevertheless, the Swift monitoring observations show that if the source went into an active state around 2007 July-August, the outburst was shorter than $\sim 3$ months, since the source was detected at lower luminosities again in 2007 late-October. For an average 2–10 keV outburst luminosity of $\sim 10^{36} \text{ erg s}^{-1}$ (the maximum value ever observed for this source), the 2–10 keV fluence of this possible outburst would have been $\lesssim 7.5 \times 10^{-4} \text{ erg cm}^{-2}$. If the system was active at a 2–10 keV luminosity of $\sim 10^{34} \text{ erg s}^{-1}$ for three months, the outburst fluence lowers to $\lesssim 7.5 \times 10^{-6} \text{ erg cm}^{-2}$ (in the 2–10 keV band).

XMM J174457–2850.3 was detected above its quiescent level several times since its discovery 7 years ago. However, it is unclear whether the source always reaches full outburst with $L_X \sim 10^{36} \text{ erg s}^{-1}$, or undergoes enhanced levels of activity with luminosities of several times $\sim 10^{33}$–$34 \text{ erg s}^{-1}$. This makes it difficult to estimate its recurrence time and outburst duration. Since 2001, XMM J174457–2850.3 was detected at outburst luminosities of $\sim 10^{36} \text{ erg s}^{-1}$ for 5 times. If we roughly assume a typical outburst duration of $\lesssim 3$ months, a lower limit for the duty cycle of the system is $\gtrsim 5\%$. For an upper limit on the activity of XMM J174457–2850.3, we may crudely estimate that it goes into outburst twice a year, in which case the duty cycle is almost 50%. Adopting a typical outburst luminosity of $\sim 10^{36} \text{ erg s}^{-1}$, then results in an estimated long-term mass-accretion rate of $1 \times 10^{-11} \text{ M}_\odot \text{ yr}^{-1} \lesssim \langle \dot{M}_{\text{long}} \rangle \lesssim 1 \times 10^{-10} \text{ M}_\odot \text{ yr}^{-1}$ for a neutron star compact primary, or $2 \times 10^{-12} \text{ M}_\odot \text{ yr}^{-1} \lesssim \langle \dot{M}_{\text{long}} \rangle \lesssim 2 \times 10^{-11} \text{ M}_\odot \text{ yr}^{-1}$ in case it is a black hole.
5 Swift observations of subluminous X-ray transients located near the Galactic centre

5.4.1 The nature of the detected transients

AX J1745.6–2901 and GRS 1741–2853 are both known X-ray bursters, which makes it very likely that these are neutron stars in LMXBs, since type-I X-ray bursts have never been detected from high-mass X-ray binaries. For AX J1745.6–2901 an LMXB nature is confirmed by its orbital period of 8.4 h. The nature of the remaining five transients is unknown. However, XMM J174457–2850.3, CXOGC J174535.5–290124 and CXOGC J174540.0–290005, all have been in outburst more than once in the past decade. This likely rules out a white dwarf accretor, since recurrent novae display outburst cycles of decades rather than years. This suggests a neutron star or black hole nature for XMM J174457–2850.3, CXOGC J174535.5–290124 and CXOGC J174540.0–290005. For CXOGC J174540.0–290005, observations reported by Wang et al. (2006) could not detect a near-IR counterpart, while the observations would have detected a main sequence star down to spectral type B5. This suggests that if CXOGC J174540.0–290005 is an X-ray binary, it is likely an LMXB.

The two new transients Swift J174553.7–290347 and Swift J174622.1–290634 were observed at 2–10 keV peak luminosities of $L_X \sim 2.0 \times 10^{35}$ erg s$^{-1}$ and $L_X \sim 7.0 \times 10^{34}$ erg s$^{-1}$, respectively. Although such luminosities are quite uncommon for white dwarf systems, Mukai et al. (2008) showed a few examples of classical novae that reach peak values of several times $10^{34}–35$ erg s$^{-1}$. Thus, in absence of other outbursts from Swift J174553.7–290347 and Swift J174622.1–290634, we cannot exclude the possibility that these two systems harbour accreting white dwarfs.

5.4.2 Subluminous X-ray transients in quiescence

The quiescent luminosity of X-ray transients sometimes holds clues to the nature of the system. The ASCA burster AX J1745.6–2901 is very likely associated with CXOGC J174535.6–290133, which was detected several times with Chandra at a level of a few times $10^{32}$ erg s$^{-1}$ (see Sect. 5.3.1). This is consistent with the neutron star nature of AX J1745.6–2901, since black hole systems with an orbital period of ~ 8 h are significantly fainter (e.g., Narayan et al. 1997; Menou et al. 1999; Lasota 2007). GRS 1741–2853 is also a confirmed neutron star system and displays a similar quiescent level of $\sim 10^{32}$ erg s$^{-1}$ (2–8 keV, Muno et al. 2003a).

The possible quiescent counterpart of the new subluminous X-ray transient Swift J174553.7–290347, the Chandra-detected X-ray source CXOGC J174553.8–290346, displays a 2–10 keV X-ray luminosity of $\sim 7 \times 10^{31} – 4 \times 10^{32}$ erg s$^{-1}$, depending on the assumed spectral model (see Sect. 5.3.4). The quiescent luminosity of XMM J174457–2850.3 is also in this regime; $\sim 10^{32}$ erg s$^{-1}$ (2–10 keV; Sakano et al. 2005). If Swift J174553.7–290347 and XMM J174457–2850.3 are X-ray binaries, their quiescent luminosities are relatively high and might point towards a neutron star nature.
5.4 Discussion

(e.g., Lasota 2007), although the orbital period of both these systems is unknown. We note that the absorption towards our transients is very high \( (> \times 10^{22} \text{ cm}^{-2}) \). Therefore, any thermal emission from the neutron star surface cannot be observed and we can only detect contributions from a powerlaw component, which is frequently observed for neutron stars at similarly low quiescent luminosities (e.g., Jonker 2008).

CXOGC J174535.5–290124 and CXOGC J174540.0–290005, two other transients, were not detected in quiescence, but have upper limits on their luminosities of \(< 9 \times 10^{30} \text{ erg s}^{-1} \) and \(< 4 \times 10^{31} \text{ erg s}^{-1} \), respectively (2–8 keV; Muno et al. 2005b). Such low quiescent luminosities are more common for black hole X-ray binaries than for neutron star systems (e.g., Garcia et al. 2001; Lasota 2007, but see Jonker et al. 2006, 2007).

5.4.3 The outbursts of subluminous X-ray transients

The disc instability model (e.g., King & Ritter 1998; Dubus et al. 1999; Lasota 2001) provides a framework to describe the outburst cycles of transient LMXBs. However, it is unclear why some X-ray transients, such as the ones discussed here, undergo outbursts with very low peak luminosities. AX J1745.6–2901 has a known orbital period of 8.4 h, which allows for a maximum luminosity of \( \sim 2 \times 10^{38} \text{ erg s}^{-1} \) (for a hydrogen-dominated disc and a neutron star mass of 1.4 \( \text{ M}_\odot \); Lasota 2007). Yet, its observed peak luminosity is over an order of magnitude lower (see Table 5.3). Since AX J1745.6–2901 displays eclipses, we must look at the system at high inclination. For several eclipsing X-ray binaries observations suggest that these are intrinsically bright but appear faint because the bright centre of the system is blocked by the outer edge of the disc and the corona (e.g., Parmar et al. 2000; Kallman et al. 2003; Muno et al. 2005a). This may also be the case for AX J1745.6–2901, for which Maeda et al. (1996) derived an inclination angle of \( i \sim 70^\circ \). To include inclination effects, the observed X-ray luminosity should be corrected by a factor \( \xi_p \), which relates to the inclination, \( i \), as \( \xi^{-1}_p = 2|\cos i| \) (Fujimoto 1988; Lapidus & Sunyaev 1985). In 2007, AX J1745.6–2901 displayed a 2–10 keV peak luminosity of \( 6.1 \times 10^{36} \text{ erg s}^{-1} \), which corrects to \( 9.2 \times 10^{36} \text{ erg s}^{-1} \) for the suggested inclination of \( i \sim 70^\circ \) (\( \xi_p \sim 1.5 \)).

It is thus conceivable that AX J1745.6–2901 is a bright X-ray transient that is obscured due to line of sight effects, although it would still seem to be at the lower end of the luminosity range for bright systems (peak luminosities of \( \sim 10^{37}–39 \text{ erg s}^{-1} \) in the 2–10 keV energy band). For comparison, the quasi-persistent neutron star system MXB 1659–29 has an orbital period of 7.1 h (Cominsky et al. 1983), which is close that of AX J1745.6–2901. However, MXB 1659–29 displays an average 2–10 keV outburst luminosity of \( 7 \times 10^{36} (D/10 \text{ kpc}) \text{ erg s}^{-1} \) (Oosterbroek et al. 2001; Sidoli et al. 2001b), which is about a factor of 4 higher than the average 2–10 keV outburst luminosity observed for AX J1745.6–2901 in 2007: \( 1.6 \times 10^{36} \text{ erg s}^{-1} \). Possibly, the
in a regime of bright X-ray transients, this does not provide an explanation for the peculiar outburst behaviour of the source. As discussed in Sect. 5.3.1, the system was likely in quiescence for several years before it was seen active in 2006 for more than 4 months. At that time, the source reached a peak luminosity of $9.2 \times 10^{35}$ erg s$^{-1}$, which would classify the system as very-faint. However, after several months of quiescence (see Figure 5.2), the source reappeared displaying a peak luminosity of $6.1 \times 10^{36}$ erg s$^{-1}$ (i.e., in the faint regime) and remained active for over 1.5 years (see Sect. 5.3.1). Thus, the outburst observed in 2006 was subluminous by about a factor of 6 compared to the 2007 outburst, yet the system maintained this low luminosity for months. It is unclear if this behaviour can be explained in terms of a disc instability model. In 1993 and 1994, different outburst luminosities of $2 \times 10^{35}$ erg s$^{-1}$ and $9 \times 10^{35}$ erg s$^{-1}$ were reported for AX J1745.6–2901 (3–10 keV, Maeda et al. 1996). This is on the same time scale as the discussed Swift detections, suggesting that the behaviour observed in 2006 and 2007 could be typical for the source.

GRS 1741–2853 also displayed two separate outbursts with very different characteristics in terms of peak luminosity and outburst duration during the Swift/XRT monitoring observations. A short, $\sim 1$–week outburst was detected in 2006, which had a 2–10 keV peak luminosity of $9.2 \times 10^{34}$ erg s$^{-1}$. A few months later, the source exhibited a much longer ($\gtrsim 13$ weeks) outburst, that reached a peak luminosity of $2.0 \times 10^{36}$ erg s$^{-1}$ (2–10 keV). Possibly, the short 2006 outburst of GRS 1741–2853 was an X-ray precursor for the 2007 outburst. Such behaviour is observed for several bright X-ray transients (both neutron star and black hole systems, see Chen et al. 1997, and references therein). Both Swift J174553.7–290347 and CXOGC J174540.0–290005 displayed short, $\sim 2$–week outbursts that had an average luminosity of a few times $10^{34}$ erg s$^{-1}$. This kind of activity resembles the small accretion outburst of GRS 1741–2853 in 2006 (see Figure 5.2), but for these two systems no longer outbursts have been observed. XMM J174457–2850.3 seems to undergo X-ray activity at different luminosity levels as well (see Sect. 5.3.7). It is unclear what causes the varying accretion luminosities. However, this phenomenon is also observed for bright X-ray transients and is thus not restricted to the subluminous systems discussed here.
5.4 Discussion

Current disc instability models do not provide an obvious explanation for accretion outbursts that last several years, rather than the usual weeks to months, such as observed for AX J1745.6–2901. A few bright systems are known to undergo quasi-persistent outbursts (see e.g., Wijnands 2004). There are also two X-ray transients that exhibit prolonged outbursts at low luminosities. XMMU J174716.1–281048 has likely been continuously active since its initial discovery in 2003, displaying a typical 2–10 keV luminosity of a few times $10^{34} \text{ erg s}^{-1}$ (e.g., Del Santo et al. 2007b; Dege- naar & Wijnands 2007). Furthermore, AX J1754.2–2754 recently made a transition to quiescence (Bassa et al. 2008), after exhibiting an accretion outburst with a 2–10 keV luminosity of several times $10^{34}–35 \text{ erg s}^{-1}$, which likely lasted for 7–8 years (Sakano et al. 2002; Del Santo et al. 2007a; Chelovekov & Grebenev 2007). This source was again found active in July 2008 (Jonker & Keek 2008). The detection of type-I X-ray bursts identifies both these systems as neutron star LMXBs, just like AX J1745.6–2901.

5.4.4 X-ray bursts from subluminous X-ray transients

The properties of type-I X-ray bursts are set by the conditions in the flash layer such as the temperature, thickness, hydrogen abundance and the fraction of carbon-nitrogen-oxygen (CNO) elements in the layer (e.g., Fujimoto et al. 1981; Bildsten 1998; Peng et al. 2007). These conditions can vary drastically as the mass-accretion rate onto the neutron star ($\dot{M}$) varies, which results in flashes with different characteristics for different $\dot{M}$ regimes (e.g., Fujimoto et al. 1981; Peng et al. 2007; Cooper & Narayan 2007).

The Swift/XRT monitoring observations of 2006 caught two type-I X-ray bursts from AX J1745.6–2901 (see Sect. 5.3.1). The average 2–10 keV luminosity of the 2006 outburst was $3.9 \times 10^{35} \text{ erg s}^{-1}$, from which we can estimate an instantaneous mass accretion rate onto the neutron star of $\sim 1 \times 10^{-10} \text{ M}_\odot \text{ yr}^{-1}$. If we include a correction factor to account for inclination effects, as discussed in Sect. 5.4.3, this value increases to $\sim 1.5 \times 10^{-10} \text{ M}_\odot \text{ yr}^{-1}$. The bursts had a duration of 50 – 60 seconds (see Figure 5.4), which suggests triggering in a mixed hydrogen/helium environment. This is in line with the classical predictions for the estimated mass-accretion rate (e.g., Fujimoto et al. 1981).

We discussed in Sect. 5.3.1, that the type-I X-ray bursts observed from AX J1745.6–2901 have 0.01–100 keV peak luminosities of $\sim 10^{38} \text{ erg s}^{-1}$, close to the Eddington limit of a neutron star. These peak values should also be corrected for the inclination effects discussed in Sect. 5.4.3. However, the X-ray burst (originating form the neutron star surface) and the outburst emission (emerging from the accretion disc) are attributed to geometrically different regions and may therefore have different degrees of isotropy (Fujimoto 1988; Lapidus & Sunyaev 1985). Although, the
X-ray burst emission will be partly intercepted and re-radiated by the accretion disc, it was shown that the degree of anisotropy is less than for the emission coming from the accretion disc (Fujimoto 1988; Lapidus & Sunyaev 1985). Inclination effects are expected to reduce the X-ray burst emission by a factor $\xi^{-1} = 0.5 + |\cos i|$ (Fujimoto 1988; Lapidus & Sunyaev 1985). For the suggested inclination of $i = 70^\circ$ (Maeda et al. 1996), we thus obtain a correction factor of $\xi_b = 1.2$. This implies peak luminosities for the type-I X-ray bursts observed from AX J1745.6–2901 on 2006 June 3 and 14 of $(1.2 - 1.6) \times 10^{38}$ erg s$^{-1}$ and $(0.62 - 1.3) \times 10^{38}$ erg s$^{-1}$ (0.01–100 keV), respectively. This is below, but close, to the Eddington luminosity for a neutron star $(2.0 \times 10^{38}$ erg s$^{-1}$ for a hydrogen-rich and $3.8 \times 10^{38}$ erg s$^{-1}$ for a hydrogen-poor photosphere; e.g., Kuulkers et al. 2003).

5.4.5 Long-term average accretion rates

Presuming that the detected transients are accreting systems, we attempted to estimate their long-term time-averaged accretion rates using the method and described in Sect. 5.2.2. We explored the scenarios of both neutron star and black hole accretors (except for AX J1745.6–2901 and GRS 1741–2853, since these are confirmed neutron star systems), which resulted in the estimated long-term mass-accretion rates listed in Table 5.4. The two confirmed neutron star systems, AX J1745.6–2901 and GRS 1741–2853 have the highest estimated accretion rates of the seven discussed transients ($\sim 10^{-11} - 10^{-10}$ M$_\odot$ yr$^{-1}$). This arises from the fact that GRS 1741–2853 is active quite regularly and AX J1745.6–2901 can be in outburst for a very long time (over 1.5 years). The regime estimated for these two sources can be well explained within current LMXB evolution models. The same is likely true for XMM J174457–2850.3, which was active several times since its discovery in 2001 and has an estimated long-term mass-accretion rate of $\gtrsim 10^{-11}$ M$_\odot$ yr$^{-1}$.

The estimates for the remaining four systems, CXOGC J174535.5–290124, CXOGC J174540.0–290005, Swift J174553.7–290347 and Swift J174622.1–290634 are much lower; $\lesssim 10^{-12}$ M$_\odot$ yr$^{-1}$ for accreting neutron stars and even an order of magnitude lower for black hole X-ray binaries, $\lesssim 10^{-13}$ M$_\odot$ yr$^{-1}$ (see Table 5.4). Comparing our results with a theoretical toy-model of King & Wijnands (2006), who explored the mechanism of Roche-lobe overflow at low accretion rates, suggests that if these transients are LMXBs, their low time-averaged mass-accretion rates might pose difficulties explaining their existence, without invoking exotic scenarios such as accretion from a planetary donor or an intermediate mass black hole as the accreting primary (King & Wijnands 2006). These are thus interesting systems to track and monitor in the future.

Apart from evolutionary scenarios and line-of-sight effects, there other possible explanations for the subluminous X-ray appearance of these transients. For example,
in particular for the systems containing a black hole, the liberated accretion power may not be primarily dissipated as X-rays but rather via radiative inefficient flows (e.g., Blandford & Begelman 1999; Fender et al. 2003; Narayan & McClintock 2008). In neutron star systems the propeller mechanism can possibly operate, so that only a small fraction of the mass transferred from the donor can be accreted onto the neutron star (e.g., Illarionov & Sunyaev 1975; Alpar 2001; Romanova et al. 2005).

AX J1745.6–2901, GRS 1741–2853 and XMM J174457–2850.3 are three examples that illustrate that X-ray transients can display different behaviour in terms of peak luminosity, outburst duration and recurrence time from year to year. It is currently not understood whether these variations should be interpreted as, e.g., being due to changes in the mass-transfer rate from the donor star or as the result of instabilities in the accretion disc. Such issues need to be resolved before we can fully comprehend the nature of subluminous X-ray transients.

Acknowledgments
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Table 5.4: Estimated outburst durations, fluences and long-term averaged accretion rates.

<table>
<thead>
<tr>
<th>Source name</th>
<th>Year</th>
<th>$t_{\text{outburst}}$ (weeks)</th>
<th>$F$ (erg cm$^{-2}$)</th>
<th>$\langle \dot{M}\rangle_{\text{NS}}$ (M$_{\odot}$ yr$^{-1}$)</th>
<th>$\langle \dot{M}\rangle_{\text{BH}}$ (M$_{\odot}$ yr$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AX J1745.6–2901</td>
<td>2006</td>
<td>&gt; 16</td>
<td>$\geq 1.8 \times 10^{-4}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2007</td>
<td>&gt; 78</td>
<td>$\geq 6.5 \times 10^{-3}$</td>
<td>$\sim (5 - 15) \times 10^{-11}$</td>
<td></td>
</tr>
<tr>
<td>CXOGC J174535.5–290124</td>
<td>2006</td>
<td>&gt; 12</td>
<td>$\geq 1.6 \times 10^{-5}$</td>
<td>$\sim (5 - 13) \times 10^{-13}$</td>
<td>$\sim (7 - 18) \times 10^{-14}$</td>
</tr>
<tr>
<td>CXOGC J174540.0–290005</td>
<td>2006</td>
<td>2</td>
<td>$1.3 \times 10^{-5}$</td>
<td>$\sim (3 - 13) \times 10^{-13}$</td>
<td>$\sim (4 - 21) \times 10^{-14}$</td>
</tr>
<tr>
<td>Swift J174553.7–290347</td>
<td>2006</td>
<td>2</td>
<td>$8.0 \times 10^{-6}$</td>
<td>$\leq 1 \times 10^{-12}$</td>
<td>$\leq 2 \times 10^{-13}$</td>
</tr>
<tr>
<td>Swift J174622.1–290634</td>
<td>2006</td>
<td>5</td>
<td>$5.0 \times 10^{-6}$</td>
<td>$\leq 4 \times 10^{-13}$</td>
<td>$\leq 6 \times 10^{-14}$</td>
</tr>
<tr>
<td>GRS 1741–2853</td>
<td>2006</td>
<td>1</td>
<td>$2.6 \times 10^{-6}$</td>
<td>$\sim (2 - 8) \times 10^{-11}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2007</td>
<td>&gt; 13</td>
<td>$\geq 1.4 \times 10^{-3}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>XMM J174457–2850.3</td>
<td>2007</td>
<td>&lt; 12</td>
<td>$\leq 7.5 \times 10^{-4}$</td>
<td>$\sim (1 - 10) \times 10^{-11}$</td>
<td>$\sim (2 - 20) \times 10^{-12}$</td>
</tr>
</tbody>
</table>

Note.– The outburst fluences are for the 2–10 keV energy band and were calculated by multiplying the mean unabsorbed outburst flux by the outburst duration. $\langle \dot{M}\rangle_{\text{NS}}$ and $\langle \dot{M}\rangle_{\text{BH}}$ are the estimated long-term averaged accretion rates for a neutron star with $M = 1.4$ M$_{\odot}$ and $R = 10$ km and a black hole with $M = 10$ M$_{\odot}$ and $R = 30$ km, respectively. AX J1745.6–2901 and GRS 1741–2853 both display type-I X-ray bursts and are thus confirmed neutron star systems.
A four-year baseline *Swift* study of enigmatic X-ray transients located near the Galactic centre

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**Abstract** – We report on continued monitoring observations of the Galactic centre carried out by the X-ray telescope aboard the *Swift* satellite in 2008 and 2009. This campaign revealed activity of the five known X-ray transients AX J1745.6–2901, CXOGC J174535.5–290124, GRS 1741–2853, XMM J174457–2850.3 and CXOGC J174538.0–290022. All these sources are known to undergo very faint X-ray outbursts with 2–10 keV peak luminosities of \( L_X^{\text{peak}} \sim 10^{34–36} \text{ erg s}^{-1} \), although the two confirmed neutron star low-mass X-ray binaries AX J1745.6–2901 and GRS 1741–2853 can also become brighter (\( L_X^{\text{peak}} \sim 10^{36–37} \text{ erg s}^{-1} \)). We discuss the observed long-term lightcurves and X-ray spectra of these five enigmatic transients. In 2008, AX J1745.6–2901 returned to quiescence following an unusually long accretion outburst of \( \sim 1.5 \) years. GRS 1741–2853 was active in 2009 and displayed the brightest outburst ever recorded for this source, reaching up to a 2–10 keV luminosity of \( L_X \sim 1 \times 10^{37} \left( D/7.2 \text{ kpc} \right)^2 \text{ erg s}^{-1} \). We find that the unclassified transient XMM J174457–2850.3 becomes bright only during short episodes (days) and is often found active in between quiescence (\( L_X \sim 10^{32} \text{ erg s}^{-1} \)) and its maximum outburst luminosity of \( L_X \sim 10^{36} \text{ erg s}^{-1} \). CXOGC J174535.5–290124 and CXOGC J174538.0–290022, as well as three other transients that were detected by this campaign in 2006, have very low time-averaged mass-accretion rates of \( \lesssim 2 \times 10^{-12} \text{ M}_\odot \text{ yr}^{-1} \). Despite having obtained two years of new data, no new X-ray transients were detected.
6 A four-year baseline Swift study of enigmatic X-ray transients

6.1 Introduction

Starting in 2006 February, the Swift satellite has been monitoring the Galactic centre (GC) with the onboard X-ray telescope (XRT; Burrows et al. 2005). In this campaign, short (∼ 1 ks) pointings are carried out on an almost daily basis\(^1\), covering a field of ∼ 26′ × 26′ of sky around Sgr A* (Kennea & The Swift/XRT team 2006; Degenaar & Wijnands 2009). This is an ideal setting for detecting transient X-ray sources in one of the most active X-ray regions in the Milky Way.

X-ray transients alternate periods of quiescence, that have a typical duration of years to decades and are characterised by 2–10 keV luminosities of ∼ \(10^{30–33}\) erg s\(^{-1}\), with occasional outbursts during which the X-ray luminosity increases by a factor \(\gtrsim 100\) for weeks to months. A large fraction of the galactic X-ray transients can be identified with neutron stars or black holes accreting matter from a companion star in an X-ray binary. Based on the nature of the donor star, we can distinguish low-mass X-ray binaries (LMXBs; \(M_{\text{donor}} \lesssim 1 M_\odot\), spectral type later than B) or high-mass X-ray binaries (HMXBs; \(M_{\text{donor}} \gtrsim 10 M_\odot\), spectral type O or B).

In LMXBs, matter is generally transferred because the donor star fills its Roche-lobe, a process that involves the formation of an accretion disc. In such systems, the transient behaviour is explained in terms of a thermal-viscous instability that causes the disc to oscillate between a cold, neutral state (quiescence), and one in which it is hot and ionized, causing a strong increase in the mass-accretion rate and resulting in an X-ray outburst (e.g., King & Ritter 1998; Lasota 2001). During quiescence, the disc regains the mass that was lost during the outburst and the cycle repeats. Symbiotic X-ray binaries form a small sub-class of LMXBs in which the compact primary, most likely a neutron star, is accreting matter from the wind of an M-type giant companion (e.g., Masetti et al. 2007).

Amongst the transient HMXBs, most of the currently known systems are Be/X-ray binaries. In such systems, the compact primary is in a wide and eccentric orbit accreting matter from the circumstellar disc surrounding a main sequence Oe or Be star around periastron passage (e.g., Negueruela 2004). However, recently Integral and RXTE have unveiled a new class of transient HMXBs, called Supergiant Fast X-ray transients (SFXTs; e.g., Negueruela et al. 2006), in which the compact star is capturing the strong stellar wind of an O or B supergiant companion. In these systems, the transient behaviour is thought to be caused by clumpy or anisotropic winds (e.g., Sidoli 2009).

The temporal and spectral properties of the brightest galactic X-ray transients, which have 2–10 keV peak luminosities of \(L_{\text{X}}^{\text{peak}} \sim 10^{36–39}\) erg s\(^{-1}\), are well estab-

\(^1\)Except during the months November–February, when the GC is too close (within 45 degrees) to the Sun.
lished through the work of numerous past and present X-ray missions. However, much less is known about transient sources that manifest themselves with lower 2–10 keV peak luminosities of \( \sim 10^{34} - 10^{36} \) erg s\(^{-1}\) (e.g., Sidoli et al. 1999; Muno et al. 2005b; Porquet et al. 2005b; Wijnands et al. 2006a; Campana 2009; Heinke et al. 2009a). It is only with the advent of the current generation of sensitive X-ray instruments that the properties of such objects can be studied in detail. To date, a few tens of low-luminosity transients are known in our Galaxy. As for the brighter systems, many of these are expected to harbour accreting neutron stars or black holes, but their nature and the underlying mechanism producing their subluminous outbursts is not understood well.

The hypothesis that a significant fraction of the low-luminosity transients are X-ray binaries, gains credence by the detection of thermonuclear X-ray bursts from several of these systems (e.g., in ’t Zand et al. 1991; Maeda et al. 1996; Cocchi et al. 1999; Cornelisse et al. 2002; Chelovekov & Grebenev 2007; Del Santo et al. 2007b; Wijnands et al. 2009). This establishes that these objects harbour accreting neutron stars, most likely in an LMXB configuration. The observed low X-ray luminosities in combination with estimates of their recurrence times, suggest that these systems have very low time-averaged mass-accretion rates (e.g., Degenaar & Wijnands 2009). This might pose a challenge to explain the existence of these LMXBs without having to invoke exotic evolutionary scenarios (e.g., King & Wijnands 2006).

Many low-luminosity transients are located within a few arcminutes of Sgr A* (e.g., Muno et al. 2005b; Wijnands et al. 2006a; Degenaar & Wijnands 2009). The Swift/GC monitoring program thus provides an excellent setting to detect new low-luminosity transients and to study the long-term behaviour of known systems. This opens up the possibility to gain more insight into their duty cycles and the energetics of their outbursts, and thereby to refine estimates of their average mass-accretion rates. This is an important parameter for understanding their evolution (e.g., King & Wijnands 2006), as well as the properties of thermonuclear X-ray bursts occurring at low accretion luminosities (e.g., in’t Zand et al. 2005b; Peng et al. 2007; Cooper & Narayan 2007).

In a previous paper, we discussed a total of seven transients that were found active during Swift/XRT monitoring observations of the GC, carried out in 2006 and 2007 (Degenaar & Wijnands 2009). Here, we discuss the data accumulated over the years 2008 and 2009, which revealed activity of five previously known X-ray transients.

6.2 Observations and data analysis

We obtained all 2008 and 2009 XRT observations of the GC from the Swift public data archive. For 2008, the nearly daily coverage resulted in a total of 171 observa-
A four-year baseline Swift study of enigmatic X-ray transients

A four-year baseline Swift study of enigmatic X-ray transients, amounting to 211 ks of exposure. All data was obtained in the photon counting (PC) mode and covers the epoch 2008 February 19–October 30. In 2009, the campaign was carried out in a slightly different setting, with ~ 1 ks observations performed once every ~ 3 days, instead of the daily repetition between 2006 and 2008. Swift targeted the GC from 2009 June 4 till November 1 during 40 observations for a total exposure time of 45 ks. Most of the 2009 data was obtained in the PC mode, apart from a selection of 3 pointings, during which the XRT was operated in the windowed timing (WT) mode. These WT observations were carried out between 2009 October 10–13, and aimed specifically for GRS 1741–2853, which was in outburst at that time and caused significant pile-up in the PC data.

All raw data were processed with the xrtpipeline using standard quality cuts and event grades 0–12 for the PC data and 0–2 for the WT mode observations. Figure 6.1 displays two accumulated X-ray images of the Swift/XRT observations. Both images clearly show regions of diffuse emission around Sgr A*, as well as several X-ray point sources. Five of these can be identified with the known X-ray transients AX J1745.6–2901, CXOGC J174535.5–290124, GRS 1741–2853, XMM J174457–2850.3 and CXOGC J174538.0–290022, while others are known persistent X-ray sources. In 2006, Swift detected three additional X-ray transients in outburst, which are not found active in the new 2008–2009 data set: CXOGC J174540.0–290005, Swift J174553.7–290347 and Swift J174622.1–290634 (Degenaar & Wijnands 2009). The locations of these transients are also indicated in Figure 6.1. We used XSELECT (v. 2.4) to compare sub-sets of the data to determine when the transients were active. A source was considered in quiescence when it was not detected by visual inspection upon summing multiple observations. A non-detection in 5 ks of data corresponds roughly to a 2–10 keV unabsorbed flux threshold of ~ 2 × 10^{-13} erg cm^{-2} s^{-1}, or a luminosity of ~ 2 × 10^{33} (D/8 kpc)^2 erg s^{-1}, although the exact value depends on the assumed spectral model.

We constructed X-ray lightcurves for the five active transients using all PC mode observations in which a source was in field of view (FOV). A circular source region with a 5 pixel radius was employed for CXOGC J174535.5–290124, XMM J174457–2850.3 and CXOGC J174538.0–290022, while a 10 pixel radius was used for the brighter AX J1745.6–2901 and GRS 1741–2853. Corresponding background events were averaged over a set of three nearby areas having the same shape and size as the source region. Particularly for sources within close proximity of Sgr A*, which are embedded in diffuse emission (see Figure 6.1), the background regions were carefully chosen to account for the enhanced background level. For AX J1745.6–2901, GRS 1741–2853 and CXOGC J174538.0–290022 we could use the full 2008–2009 data set to create the X-ray lightcurve. However, for both CXOGC J174535.5–290124 (which is only visible when AX J1745.6–2901 is quiescent) and XMM J174457–
6.2 Observations and data analysis

Figure 6.1: Swift/XRT PC mode images (0.3–10 keV) of the region around Sgr A∗. The images indicate the locations of the five X-ray transients that were in outburst in 2008–2009, as well as three additional transients that were detected with Swift in 2006 (CXOGC J174540.0–290005, Swift J174553.7–290347 and Swift J174622.1–290634). Left) Merged X-ray image of the data obtained in 2008 and 2009. Right) A magnified image of the inner region around Sgr A∗ from the epoch between 2008 September 2 and 2009 November 1, during which AX J1745.6–2901 resided in quiescence and activity from CXOGC J174535.5–290124 could be detected. CXOGC J174538.0–290022 was also detected in outburst during that time.

2850.3 (which has a large offset from Sgr A∗ and was therefore not always in FOV), the lightcurve was constructed from a sub-set of the observations. We combined the 2008–2009 data with that of 2006–2007 (discussed in Degenaar & Wijnands 2009), to obtain lightcurves with a four-year long baseline for the five active transients. These are displayed in Figure 6.2.

The PC data of AX J1745.6–2901 and GRS 1741–2853 are subject to pile-up. This effect becomes an issue for PC mode count rates above ~ 0.5 counts s⁻¹ and causes multiple photons to be registered as single events, thus underestimating the true count rate. The lightcurves of AX J1745.6–2901 and GRS 1741–2853 are not corrected for this. To estimate to which extent the count rates are affected, we subtracted source events from both circular and annular regions for the piled-up data of both sources. By comparing the fluxes deduced from spectral fitting, we find that pile-up causes the PC mode count rates to be underestimated by a factor of ~ 1.2 at ~ 0.7 counts s⁻¹, ~ 1.5 at ~ 1.0 counts s⁻¹ (about the peak count rate of AX J1745.6–2901) and ~ 3 at ~ 1.8 counts s⁻¹ (the peak count rate observed for GRS 1741–2853).

We combined all the pointings in which a source was active to create a summed outburst spectrum (displayed in Figure 6.3). For AX J1745.6–2901 and GRS 1741–2853, we attempted to circumvent the effect of pile-up on the spectral shape by using
an annular extraction region for the PC data, following the Swift pile-up analysis thread. As such, we used an annulus with an inner (outer) radius of 6 (15) pixels to extract source events from AX J1745.6–2901, and an inner (outer) radius of 7 (30) pixels for GRS 1741–2853. We compared the pile-up corrected PC spectra of GRS 1741–2853 with spectra obtained from quasi-simultaneous WT mode data, which are not subject to pile-up. For the WT data, we used a 40 × 40 pixels rectangular extraction region for source events, and a box of similar dimensions as a background reference. From spectral fitting, we obtained fluxes for the different modes that differ by ~ 10%, and spectral parameters that are consistent with one another within the errors. This suggests that the above described pile-up correction for the PC mode works satisfactorily.

Using the software tool xrtexpmap, we generated exposure maps for each observation, which carry information about the bad columns and hence the effective area of the CCD. These were subsequently used to create ancillary response files (arf) for all spectra with the task xrtmkarf. These account for different extraction regions, vignetting and corrections for the point spread function. The latest response matrix files (rmf, v. 11) were taken from the CALDB database. Using grppha, the spectra were grouped to contain at least 20 photons per bin. However, for XMM J174457–2850.3 and CXOGC J174535.5–290124 we use bins with a minimum of 10 photons, because of the low number of counts collected for these two sources.

We fitted the average outburst spectra using Xspec (v. 12.5; Arnaud 1996) to an absorbed powerlaw model and deduce the absorbed and unabsorbed fluxes in the 2–10 keV energy range. For the neutral hydrogen absorption, we use the phabs model using the default Xspec abundances and cross-sections. When a source displayed multiple outbursts, we fitted these simultaneously with the hydrogen column density tied. We include the 2006 and 2007 data (discussed in Degenaar & Wijnands 2009) in these fits. To calculate the unabsorbed peak flux of the outbursts of AX J1745.6–2901, XMM J174457–2850.3 and GRS 1741–2853, we extracted a single spectrum from the observation with the highest count rate. For the former two we use PC observations, applying pile-up corrections as described above when necessary, while for the latter source WT data was available. In case of CXOGC J174535.5–290124 and CXOGC J174538.0–290022, the source count rates were too low to extract a spectrum from a single observation. Therefore, we determined a count rate to flux conversion factor for these two sources by comparing the average outburst flux with the average net count rate. We then used this to estimate the unabsorbed peak flux from the observed peak count rate.

All five active X-ray transients are heavily absorbed ($N_\text{H} \gtrsim 7 \times 10^{22}$ cm$^{-2}$; see Table 6.1), consistent with values obtained for sources that lie close to Sgr A*. We

\footnote{http://www.swift.ac.uk/pileup.shtml.}
therefore assumed source distances of 8 kpc when calculating 2–10 keV luminosities from the unabsorbed fluxes. However, for GRS 1741–2853 we use a distance of 7.2 kpc, since this is the upper limit that has recently been inferred from the analysis of thermonuclear X-ray bursts (Trap et al. 2009). The X-ray spectra are displayed in Figure 6.3 and the results of our spectral analysis are presented in Table 6.1. The 2006 and 2007 data (reported by Degenaar & Wijnands 2009), are refitted here.

For each observed outburst we calculate the fluence by multiplying the average unabsorbed 2–10 keV outburst flux with the duration of the outburst. These results are presented in Table 6.2. Assuming that the transients are accreting systems, we additionally calculate the mass-accretion rates during outburst. Furthermore, we use the estimated duty cycles to obtain an order of magnitude approximation for their long-term mass-accretion rates (see Section 6.4.2 for further details). These results are also included in Table 6.2.

6.3 X-ray lightcurves and spectra

6.3.1 AX J1745.6–2901

The X-ray transient AX J1745.6–2901 was detected with the ASCA satellite in 1993 October and in 1994 October, displaying 3–10 keV luminosities of \( \sim 2 \times 10^{35} \) and \( \sim 9 \times 10^{35} \) erg s\(^{-1}\), respectively (Maeda et al. 1996). The detection of thermonuclear X-ray bursts identified the source as a neutron star LMXB and the system displays eclipses with a period of 8.4 h, which represents the binary orbital period (Maeda et al. 1996). The likely quiescent counterpart, CXOGC J174535.6–290133, has a 2–10 keV luminosity of several times \( 10^{32} \) erg s\(^{-1}\) (Degenaar & Wijnands 2009).

Since 1994, AX J1745.6–2901 was never reported in outburst again, despite regular monitoring of the GC, e.g., with the Chandra satellite between 1999 and 2004 (Muno et al. 2003b, 2004, 2005b). However, the source was found active in 2006 February, when the Swift/XRT monitoring observations of the GC kicked off (Kennea et al. 2006a).\(^3\) AX J1745.6–2901 remained active for 16 weeks at an average 2–10 keV luminosity of \( \sim 4 \times 10^{35} \) erg s\(^{-1}\) (Degenaar & Wijnands 2009, see also Table 6.1). Subsequently, the source resided in quiescence for at least four months (2006 July–October), but was again detected in outburst by Integral and Swift on 2007 February 15–17 (Kuulkers et al. 2007a; Wijnands et al. 2007). The activity continued throughout the 2007 monitoring campaign, which ended on 2007 November 2. The average outburst luminosity was \( \sim 1.5 \times 10^{36} \) erg s\(^{-1}\) (2–10 keV), i.e.,

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\(^3\)The transient was first denoted as Swift J174535.5–290135, but the detection of 8.4 hr eclipses in XMM-Newton observations definitely linked Swift J174535.5–290135 to AX J1745.6–2901 (Porquet et al. 2007).
Figure 6.2: Background corrected 0.3–10 keV Swift/XRT lightcurves of the five transients that were active in 2008–2009 (PC mode data only). Displayed is their long-term behaviour from the start of the monitoring campaign of the GC on 2006 February 24. Days 0–616 cover the years 2006 and 2007 (discussed in Degenaar & Wijnands 2009), whereas days 725–1346 represent the new data assembled in 2008–2009. The lightcurve of GRS 1741–2853 shows a magnified image of the short and weak outburst that occurred in 2006.
approximately 4 times higher than the level observed in 2006 (Porquet et al. 2007; Degenaar & Wijnands 2009).

When the Swift/GC monitoring observations resumed on 2008 February 19, AX J1745.6–2901 was detected at a similar intensity as measured in 2007 November (see Figure 6.2). This makes it likely that the outburst continued during the time that Swift could not observe the GC due to Sun-angle constraints. In 2008, the source flux was observed to decrease gradually (see Figure 6.2). In late-August, the decay accelerated and within two weeks the source luminosity dropped from $\sim 10^{36}$ erg s$^{-1}$ (2–10 keV), down to the background level on 2008 September 2. AX J1745.6–2901 was not detected for the remainder of the Swift/XRT observations in 2008 and the system had thus returned to quiescence following an accretion outburst that lasted > 1.5 years (> 80 weeks). In 2009, no activity was detected, indicating that the source remained in quiescence. However, in 2010 June the source is again detected in outburst by Swift/XRT at a 2–10 keV luminosity of a few times $10^{35}$ erg s$^{-1}$ (Degenaar et al. 2010c).

The different outburst spectra of AX J1745.6–2901 are displayed in Figure 6.3. Both the 2006 and 2007–2008 outburst have a soft X-ray spectrum with powerlaw indices of $\Gamma = 2.4 \pm 0.1$ and $2.7 \pm 0.1$, respectively (see Table 6.1). The 2006 outburst appears to have a harder X-ray spectrum than the brighter 2007–2008 outburst (we obtain similar results when $N_H$ is left as a free parameter and not fixed between the outbursts). The spectra indicate that the system is heavily absorbed with a best fit hydrogen column density of $N_H = (23.8 \pm 0.5) \times 10^{22}$ cm$^{-2}$. The average 2–10 keV
unabsorbed flux during the 2007–2008 outburst was \( \sim 1 \times 10^{-10} \) erg cm\(^{-2}\) s\(^{-1}\). For an outburst duration of \( > 80 \) weeks, this implies a fluence of \( \gtrsim 7 \times 10^{-3} \) erg cm\(^{-2}\), which is a factor of \( \sim 10 \) higher than that of the 2006 outburst (see Table 6.2).

### 6.3.2 CXOGC J174535.5–290124

The X-ray source CXOGC J174535.5–290124 is located only \( \sim 14'' \) away from AX J1745.6–2901 (see Figure 6.1). This transient was discovered in 2001 during a monitoring campaign of the GC with Chandra (Muno et al. 2004). Since then, the source has been detected in outburst multiple times with Chandra, XMM-Newton and Swift, displaying typical luminosities of \( \sim 10^{33–34} \) erg s\(^{-1}\) (Muno et al. 2005b; Wijnands et al. 2005c, 2006b; Degenaar et al. 2008a; Degenaar & Wijnands 2009). In quiescence, the source has not been detected, yielding an upper limit on luminosity of \( < 9 \times 10^{30} \) erg s\(^{-1}\) (2–8 keV; Muno et al. 2005b).

Swift/XRT cannot spatially resolve CXOGC J174535.5–290124 and AX J1745.6–2901 when the latter, which is the brightest of the two, is active. We can therefore only deduce information on the activity of CXOGC J174535.5–290124 from Swift data obtained in epochs that AX J1745.6–2901 is quiescent, which is 2006 July–November and 2008 September onwards (see Section 6.3.1). In 2006, the Swift/XRT observations captured an outburst from CXOGC J174535.5–290124 that had a duration of \( > 12 \) weeks (Degenaar & Wijnands 2009).

Renewed activity of CXOGC J174535.5–290124 was revealed by Chandra observations obtained on 2008 May 10–11, when the source displayed a 2–10 keV luminosity of a few times \( 10^{33} \) erg s\(^{-1}\) (Degenaar et al. 2008b). After AX J1745.6–2901 had returned to quiescence in 2008 September, CXOGC J174535.5–290124 was continuously detected until the monitoring observations ended on 2008 October 30. This outburst thus lasted for \( > 8 \) weeks. If the activity observed by Swift/XRT was part of the same outburst that was detected by Chandra in 2008 May, the outburst duration increases to \( > 24 \) weeks. Alternatively, if the source returned to quiescence in between, the dormant phase must have lasted \( < 18 \) weeks. The source was not found active during the 2009 observations (see Figure 6.2).

The average 2–10 keV unabsorbed flux observed with Swift/XRT in 2008 was \( \sim 1 \times 10^{-12} \) erg cm\(^{-2}\) s\(^{-1}\), a factor \( \sim 1.5 \) lower than observed in 2006 (see Table 6.1). For an outburst duration of \( > 8 \) weeks, we can constrain the fluence of the 2008 outburst to be \( > 7 \times 10^{-6} \) erg cm\(^{-2}\) (2–10 keV). This increases to \( > 2 \times 10^{-5} \) erg cm\(^{-2}\) if the outburst endured for more than 24 weeks. The spectrum of CXOGC J174535.5–290124 is heavily absorbed \( (N_H = (12.0 \pm 6.9) \times 10^{22} \) cm\(^{-2}\)) and for both outbursts we obtain a rather hard spectral index of \( \Gamma \sim 1 \), although the uncertainties on this parameter are very large (see Table 6.1). The X-ray spectra of the 2006 and 2008 outbursts are shown in Figure 6.3.
Figure 6.3: Background corrected Swift/XRT average outburst spectra. For AX J1745.6–2901, CXOGC J174535.5–290124 and GRS 1741–2853, spectra of the different outbursts captured during the 2006–2009 Swift/XRT monitoring are plotted together. The plot of XMM J174457–2850.3 shows the average outburst spectrum of the source in 2008, as well as the spectrum of the low-level activity observed in the months following this outburst.
6.3.3 GRS 1741–2853

GRS 1741–2853 was discovered in 1990 March–April by the Granat satellite (Sunyaev 1990). Since then, the system has been detected in outburst on multiple occasions with 2–10 keV luminosities of \( \sim 10^{36} \) erg s\(^{-1}\) (e.g., Sakano et al. 2002; Muno et al. 2003a; Wijnands et al. 2006a; Trap et al. 2009). In quiescence the source displays a luminosity of \( \sim 10^{32} \) erg s\(^{-1}\) (Muno et al. 2003a). The detection of thermonuclear X-ray bursts by BeppoSAX established that this system is an LMXB harbouring a neutron star (Cocchi et al. 1999).

Between 2006 September 14–20, the Swift/XRT monitoring observations detected a short (\( \sim 1 \) week) outburst from GRS 1741–2853, which reached a 2–10 keV peak luminosity of only \( \sim 9 \times 10^{34} \) erg s\(^{-1}\). This is markedly lower than other outbursts observed from this source (\( L_X \sim 10^{36}–37 \) erg s\(^{-1}\)). In 2007 February–April, the source experienced a longer (>13 weeks) and brighter (2–10 keV peak \( L_X \sim 2 \times 10^{36} \) erg s\(^{-1}\)) outburst, which was captured by several satellites (Kuulkers et al. 2007b; Porquet et al. 2007; Muno et al. 2007b; Degenaar & Wijnands 2009).

GRS 1741–2853 remained dormant throughout the 2008 Swift monitoring campaign (see Figure 6.2), but experienced another accretion outburst in 2009 October, which was registered by Integral and Swift (Chenevez et al. 2009b; Kennea 2009). While GRS 1741–2853 was not detected during Swift/XRT observations performed on 2009 September 23, it was found active on 2009 September 29 and the flux started to rise in the following days (Kennea 2009, see also Figure 6.2). The source intensity had decayed to the background level during the last observation of the campaign, performed on 2009 November 1. This suggests that the 2009 outburst had a duration of 4–5 weeks. The outburst reached a peak luminosity of \( \sim 1 \times 10^{37} \) erg s\(^{-1}\), while the average outburst value was \( \sim 2 \times 10^{36} \) erg s\(^{-1}\) (2–10 keV; see Table 6.1). To our knowledge, this is the highest peak luminosity ever reported for GRS 1741–2853.

By fitting the data of the three outbursts simultaneously, we obtain a hydrogen column density of \( N_H = (14.0 \pm 0.7) \times 10^{22} \) cm\(^{-2}\). The X-ray spectra, displayed in Figure 6.3, are soft with powerlaw indices of \( \Gamma = 5.0 \pm 2.5, 2.6 \pm 0.1 \) and \( 3.0 \pm 0.2 \) for the 2006, 2007 and 2009 activity, respectively. The uncertainty on the spectral index of the short and weak 2006 outburst is very large, but comparing the 2007 and 2009 outburst data suggests that the X-ray spectrum is softer for the brightest of the two outbursts. Using a duration of 4–5 weeks and an average unabsorbed flux of \( \sim 2.8 \times 10^{-10} \) erg cm\(^{-2}\) s\(^{-1}\) (see Table 6.1), we can estimate that the 2009 outburst of GRS 1741–2853 had a 2–10 keV fluence of \( \sim 8 \times 10^{-4} \) erg cm\(^{-2}\). Despite the different outburst duration and peak luminosity, this is comparable to the 2007 outburst observed by Swift/XRT (see Table 6.2).
6.3 X-ray lightcurves and spectra

Table 6.1: Results from fitting the X-ray spectral data.

<table>
<thead>
<tr>
<th>Source name</th>
<th>Year</th>
<th>$N_{\text{H}}$</th>
<th>$\Gamma$</th>
<th>$\chi^2$ (d.o.f.)</th>
<th>$F_{\text{X,abs}}^\text{peak}$</th>
<th>$F_{\text{X,unabs}}^\text{peak}$</th>
<th>$L_{\text{X,peak}}^\text{peak}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>AX J1745.6–2901</td>
<td>2008</td>
<td>23.8 ± 0.5</td>
<td>2.7 ± 0.1</td>
<td>1.10 (1427)</td>
<td>22.5 ± 0.2</td>
<td>93.2 ± 5.5</td>
<td>710</td>
</tr>
<tr>
<td></td>
<td>2007</td>
<td>23.8 ± 0.5</td>
<td>2.7 ± 0.1</td>
<td>1.10 (1427)</td>
<td>45.2 ± 0.3</td>
<td>187.7 ± 7.5</td>
<td>800</td>
</tr>
<tr>
<td></td>
<td>2006</td>
<td>23.8 ± 0.5</td>
<td>2.4 ± 0.1</td>
<td>1.10 (1427)</td>
<td>14.8 ± 0.2</td>
<td>53.3 ± 2.2</td>
<td>120</td>
</tr>
<tr>
<td>CXOGC J174535.5–290124</td>
<td>2008</td>
<td>12.0 ± 6.9</td>
<td>1.0 ± 1.6</td>
<td>1.23 (25)</td>
<td>0.9 ± 0.3</td>
<td>1.4 ± 0.6</td>
<td>2.6</td>
</tr>
<tr>
<td></td>
<td>2006</td>
<td>12.0 ± 6.9</td>
<td>0.8 ± 1.0</td>
<td>1.23 (25)</td>
<td>1.3 ± 0.2</td>
<td>2.1 ± 0.6</td>
<td>4.0</td>
</tr>
<tr>
<td>GRS 1741–2853</td>
<td>2009</td>
<td>14.0 ± 0.7</td>
<td>3.0 ± 0.2</td>
<td>0.99 (416)</td>
<td>87.2 ± 1.5</td>
<td>283.6 ± 2.2</td>
<td>2200</td>
</tr>
<tr>
<td></td>
<td>2007</td>
<td>14.0 ± 0.7</td>
<td>2.6 ± 0.1</td>
<td>0.99 (416)</td>
<td>61.7 ± 1.0</td>
<td>174.9 ± 1.2</td>
<td>260</td>
</tr>
<tr>
<td></td>
<td>2006</td>
<td>14.0 ± 0.7</td>
<td>5.0 ± 2.5</td>
<td>0.99 (416)</td>
<td>0.6 ± 0.3</td>
<td>5.0 ± 3.7</td>
<td>12</td>
</tr>
<tr>
<td>XMM J174457–2850.3</td>
<td>2009</td>
<td>7.5 ± 2.9</td>
<td>2.3 ± 1.1</td>
<td>0.83 (29)</td>
<td>11.5 ± 1.8</td>
<td>21.3 ± 6.4</td>
<td>21.8</td>
</tr>
<tr>
<td></td>
<td>2008</td>
<td>7.5 ± 2.9</td>
<td>1.6 ± 0.6</td>
<td>0.83 (29)</td>
<td>20.7 ± 2.0</td>
<td>32.4 ± 5.4</td>
<td>250</td>
</tr>
<tr>
<td></td>
<td>–low</td>
<td>7.5 ± 2.9</td>
<td>1.8 ± 1.4</td>
<td>0.83 (29)</td>
<td>0.5 ± 0.2</td>
<td>0.8 ± 0.2</td>
<td>3.6</td>
</tr>
<tr>
<td></td>
<td>2007</td>
<td>7.5 fix</td>
<td>1.8 fix</td>
<td>1.14 (21)</td>
<td>2.7 ± 0.5</td>
<td>5.0 ± 1.4</td>
<td>21.8</td>
</tr>
<tr>
<td>CXOGC J174538.0–290022</td>
<td>2009</td>
<td>12.8 ± 5.9</td>
<td>1.4 ± 0.9</td>
<td>1.14 (21)</td>
<td>2.7 ± 0.5</td>
<td>5.0 ± 1.4</td>
<td>21.8</td>
</tr>
</tbody>
</table>

Note.—For sources that displayed multiple outbursts, we fitted the different outburst spectra simultaneously with the hydrogen column density (given in units of 10$^{22}$ cm$^{-2}$) tied. The 2006 and 2007 data (discussed by Degenaar & Wijnands 2009) are re-fitted in this work. Fluxes and luminosities are for the 2–10 keV energy band and given in units of 10$^{-12}$ erg cm$^{-2}$ s$^{-1}$ and 10$^{-34}$ erg s$^{-1}$, respectively. $F_{\text{X,abs}}$ and $F_{\text{X,unabs}}$ represent the mean absorbed and unabsorbed outburst fluxes, while $L_{\text{X,peak}}$ is the unabsorbed peak flux. $L_{\text{X}}$ and $L_{\text{X,peak}}$ are the average and peak outburst luminosity, respectively. These are calculated from the unabsorbed fluxes by adopting a distance of 7.2 kpc for GRS 1741–2853 and 8 kpc for all other sources. Fluxes for the 2007 activity of XMM J174457–2850.3 were deduced using ratios, for fixed values of $N_{\text{H}}$ and $\Gamma$.

6.3.4 XMM J174457–2850.3

XMM J174457–2850.3 is a transient X-ray source that was first detected in outburst with XMM-Newton in 2001 September, when it displayed a 2–10 keV luminosity of $\sim 5 \times 10^{34}$ erg s$^{-1}$ (Sakano et al. 2005). Since its initial discovery, XMM J174457–2850.3 has been active repeatedly, displaying 2–10 keV X-ray luminosities in a broad range of a few times $\sim 10^{33}$ erg s$^{-1}$, up to $\sim 10^{36}$ erg s$^{-1}$ (Wijnands et al. 2006a; Muno et al. 2007b).

As mentioned earlier, XMM J174457–2850.3 is only in FOV in a sub-set of the Swift/XRT monitoring data, due to its relatively large offset from Sgr A$^*$ ($\sim 13.7\arcmin$).
The source was never in FOV during the 2006 observations. In 2007, the source field was covered a few times between July and November, and XMM J174457–2850.3 was detected at 2–10 keV luminosities of $\sim 10^{33-34}$ erg s$^{-1}$ (Degenaar & Wijnands 2009). When the source first came into view in 2008, on June 28, it displayed a 2–10 keV X-ray luminosity of $\sim 1 \times 10^{36}$ erg s$^{-1}$. The source intensity decreased over the course of a few days, down to a level of a few times $10^{33}$ erg s$^{-1}$ around 2008 July 7 (see Figure 6.2).

Following this decay, the source remained to be detected by Swift/XRT all through the end of the monitoring observations on 2008 October 30. During this episode, XMM J174457–2850.3 displayed a 2–10 keV luminosity of a few times $10^{33}$ erg s$^{-1}$, which is a factor $> 10$ above its quiescent level of $\sim 10^{32}$ erg s$^{-1}$ (Sakano et al. 2005). We extracted separate spectra of the bright outburst (2008 June 28–July 7), as well as the low-level activity that followed (2008 July 8–October 30). Both spectra are shown in Figure 6.3 and the spectral parameters and fluxes are listed in Table 6.1. We note that the source is not detected in our Chandra monitoring observations of the GC performed on 2008 May 10 (Degenaar et al. in preparation), which implies that the 2–10 keV luminosity of XMM J174457–2850.3 was lower than a few times $10^{33}$ erg s$^{-1}$ at that time. The bright active state (2–10 keV luminosity of $\sim 10^{35-36}$ erg s$^{-1}$) detected in 2008 late-June thus lasted < 49 days (< 7 weeks).

In 2009, the source was detected during a single Swift pointing performed on September 29, at a luminosity of $\sim 2 \times 10^{35}$ erg s$^{-1}$ (2–10 keV). The spectrum of this observation largely overlays the average spectrum of the 2008 outburst and is therefore not plotted in Figure 6.3. XMM J174457–2850.3 is not active in the preceding, nor in the subsequent observation, carried out on September 23 and October 2, respectively. This implies that the activity lasted less than 9 days.

For the different outbursts captured by Swift between 2006–2009, we obtain spectral parameters that are comparable to the outburst values reported by Sakano et al. (2005) using XMM-Newton and Chandra data obtained in 2001. The source is heavily absorbed ($N_H = (7.5 \pm 2.9) \times 10^{22}$ cm$^{-2}$) and the powerlaw index adapts values of $\Gamma \sim 1.5 - 2.5$, with large uncertainties due to the low statistics (see Table 6.1). There is no obvious correlation between the spectral index and the source flux. The 2–10 keV fluence of the different outbursts of XMM J174457–2850.3 varies between $\sim (0.4 - 10) \times 10^{-5}$ erg cm$^{-2}$ (see Table 6.2), with an average value of $\sim 2.5 \times 10^{-5}$ erg cm$^{-2}$.

6.3.5 CXOGC J174538.0–290022

The X-ray source CXOGC J174538.0–290022 was discovered during Chandra monitoring observations of the GC (Muno et al. 2003b). Between 1999 and 2004, Chandra detected the source at a minimum and maximum luminosity of $\sim 1 \times 10^{33}$ and
~ $3 \times 10^{34}$ erg s$^{-1}$, respectively (2–8 keV; Munoz et al. 2005b). The source was not detected during the Swift/XRT monitoring observations carried out in 2006, 2007 and 2008 (see Figure 6.2).

CXOGC J174538.0–290022 was reported active as seen during XMM-Newton observations obtained between 2009 April 1–5, displaying a 2–10 keV luminosity of ~ $2 \times 10^{34}$ erg s$^{-1}$ (Ponti et al. 2009). A ~ 4.6 ks Swift/XRT ToO pointing performed on 2009 May 17, about 6 weeks after the XMM-Newton detection, found the source still in outburst. The Swift monitoring observations of the GC resumed on 2009 June 4, and the source is clearly detected by visual inspection until 2009 mid-July. The average luminosity during this episode is ~ $9 \times 10^{34}$ erg s$^{-1}$, peaking at ~ $2 \times 10^{35}$ erg s$^{-1}$ (2–10 keV).

Although no clear source activity is apparent in individual exposures obtained after 2009 mid-July, summing the data from this period till the end of the monitoring observations (2009 November 1), does result in a weak detection of the source. The average luminosity during this episode is ~ $1 \times 10^{34}$ erg s$^{-1}$. Figure 6.3 displays the average Swift/XRT spectrum of the entire active period, i.e., from 2009 May–November. The spectral parameters and fluxes are listed in Table 6.1.

The outburst captured by Swift had a duration of > 9 weeks. It is likely that the source was continuously active between the XMM-Newton detection and the Swift/XRT observations, which would imply that the outburst had a duration of more than 30 weeks. We note that the source is not detected during the 2010 monitoring observations, which commenced on 2010 April 4. This implies that the outburst of CXOGC J174538.0–290022 was shorter than 52 weeks. The spectral parameters deduced from fitting the XRT data ($N_H = (12.8 \pm 5.9) \times 10^{22}$ cm$^{-2}$ and $\Gamma = 1.4 \pm 0.9$; see Table 6.1) are similar to the values inferred from XMM-Newton observations obtained in 2008 early-April (Ponti et al. 2009). If we assume an outburst duration of 30–52 weeks, the average unabsorbed flux of ~ $5 \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$ implies a 2–10 keV outburst fluence of ~ $(9 - 20) \times 10^{-5}$ erg cm$^{-2}$ (see Table 6.2).

6.4 Discussion

In this work, we analysed the lightcurves and spectra of five different X-ray transients that were found active during Swift/XRT monitoring observations of the GC carried out in 2008 and 2009. The four sources AX J1745.6–2901, CXOGC J174535.5–290124, GRS 1741–2853 and XMM J174457–2850.3 were also active between 2006 and 2007, while CXOGC J174538.0–290022 was detected for the first time with Swift in 2009. The two brightest transients, AX J1745.6–2901 and GRS 1741–2853, are both confirmed neutron star LMXBs (based on the detection of thermonuclear X-ray bursts), while the other three are unclassified X-ray sources.
AX J1745.6–2901 was observed to return to quiescence in 2008 September, following an unusually long accretion episode that started before 2007 February and endured for \( \gtrsim 1.5 \) years. In 2009, the \textit{Swift}/XRT observations captured the brightest outburst ever reported for GRS 1741–2853, which reached up to a 2–10 keV peak luminosity of \( 1.3 \times 10^{37} \text{ erg s}^{-1} \). Both sources appear to have rather soft X-ray spectra with powerlaw indices that are higher (\( \Gamma \sim 2.5 – 3.0 \); see Table 6.1) than typically found for brighter neutron star LMXBs (\( \Gamma \sim 2 \)). Furthermore, the 2008–2009 data set reveals that although XMM J174457–2850.3 exhibits outbursts with peak luminosities around \( \sim 1 \times 10^{36} \text{ erg s}^{-1} \), it can also spend long episodes at a much lower active level of \( \sim 10^{33–34} \text{ erg s}^{-1} \) (2–10 keV).

CXOGC J174535.5–290124 and CXOGC J174538.0–290022 both display very low 2–10 keV peak luminosities of \( \sim 10^{34–35} \text{ erg s}^{-1} \) and have never been detected at higher levels. CXOGC J174535.5–290124 was active in 2008, while a previous outburst was detected with \textit{Swift}/XRT in 2006 (Degenaar & Wijnands 2009). This confirms that this system has a relatively high duty cycle. CXOGC J174538.0–290022 displayed an outburst peak luminosity of \( \sim 2 \times 10^{35} \text{ erg s}^{-1} \) (2–10 keV), which is \( \sim 2 \) orders of magnitude higher than the lowest luminosity detected during \textit{Chandra} observations of the GC carried out between 1999 and 2004 (\( \sim 1 \times 10^{33} \text{ erg s}^{-1} \) in the 2–8 keV band; Muno et al. 2005b). This unambiguously demonstrates the transient nature of this source. If CXOGC J174538.0–290022 is an X-ray binary and its quiescent luminosity is \( \sim 1 \times 10^{33} \text{ erg s}^{-1} \) (Muno et al. 2005b), this would favour a neutron star as the compact primary, since black hole systems are typically fainter in their quiescent states unless the orbital period is several days (e.g., Narayan et al. 1997; Menou et al. 1999; Lasota 2007).

In 2006, the \textit{Swift}/XRT monitoring campaign of the GC detected activity of three other transients, CXOGC J174540.0–290005, Swift J174553.7–290347 (likely associated to CXOGC J174553.8–290346) and Swift J174622.1–290634 (Degenaar & Wijnands 2009). The former two both experienced short outbursts (\( \sim 2 \) weeks) with 2–10 keV peak luminosities of \( \sim 2 \times 10^{35} \text{ erg s}^{-1} \). These two sources are not detected during the 2008–2009 observations, which confirms that these systems have low duty cycles (Degenaar & Wijnands 2009, see also Table 6.2). The newly discovered transient Swift J174622.1–290634 was active for \( \sim 5 \) weeks in 2006 and reached a peak luminosity of \( \sim 7 \times 10^{34} \text{ erg s}^{-1} \) (2–10 keV). This source has a relatively large offset from Sgr A* (\( \sim 11' \)) and was only in FOV during 39 and 4 pointings in 2008 and 2009, respectively. No activity is detected from the source during these observations.
6.4 Discussion

6.4.1 Peculiar source properties

Lightcurve morphology of AX J1745.6–2901

As discussed in Section 6.3.1, the *Swift* /XRT observations of the GC exposed two distinct outbursts from AX J1745.6–2901 between 2006 and 2009, which are very different in terms of duration and luminosity (see Tables 6.1 and 6.2). Since AX J1745.6–2901 is a confirmed neutron star LMXB, the disc instability model is thought to provide the framework to explain the outburst behaviour of this source.

The average 2–10 keV luminosity during the 2007–2008 outburst was \( \sim 1 \times 10^{36} \text{ erg s}^{-1} \) (see Table 6.1). Assuming that the bolometric luminosity is a factor of \( \sim 3 \) higher (e.g., in’t Zand et al. 2007), this implies a mass-accretion rate of \( \langle \dot{M} \rangle_{\text{ob}} \sim 3 \times 10^{-10} \text{ M}_\odot \text{ yr}^{-1} \) for a canonical neutron star with \( M = 1.4 \text{ M}_\odot \) and \( R = 10 \text{ km} \). For an outburst duration of 1.5 years, this corresponds to a total accreted disc mass of \( \sim 5 \times 10^{-10} \text{ M}_\odot \). In 2006, the outburst had an average luminosity of \( \sim 4 \times 10^{35} \text{ erg s}^{-1} \) and a duration of \( > 16 \) weeks, which would translate into a mean mass-accretion rate of \( \langle \dot{M} \rangle_{\text{ob}} \sim 1 \times 10^{-10} \text{ M}_\odot \text{ yr}^{-1} \) and a total accreted mass of \( \gtrsim 3 \times 10^{-11} \text{ M}_\odot \).

Given the fact that AX J1745.6–2901 is transient, the mass-transfer rate from the companion star must be lower than the accretion rate onto the compact object during outburst (e.g., King & Ritter 1998), i.e., \( \langle \dot{M} \rangle_{\text{tr}} \lesssim 1 \times 10^{-10} \text{ M}_\odot \text{ yr}^{-1} \) (as estimated from the 2006 outburst; see Table 6.2). If the mass-transfer rate from the companion star does not change considerably over time, it would thus take the system at least 5 years to build up the accretion disc that powered the 2007–2008 outburst from scratch. This is consistent with the fact that no similarly long outbursts from this source have been observed between 1994 and 2006 (see Section 6.3.1). The duty cycle of similar 1.5-year long outbursts from this system would thus be \( \lesssim 23\% \). This is in agreement with observational constraints, which result in an estimated duty cycle of \( 10 \sim 30\% \) (Degenaar & Wijnands 2009). Given the time required to build up an accretion disc that can account for the 2007–2008 activity, and the observed quiescence interval between the 2006 and 2007–2008 outbursts of only \( \sim 4 \sim 7 \) months (Degenaar & Wijnands 2009, see also Figure 6.2), it seems that a significant residual accretion disc must have remained after the 2006 outburst ended. Shorter outbursts like the one observed in 2006 consume much less disc mass and could recur on a time scale of a only a few months. As mentioned in Section 6.3.1, AX J1745.6–2901 was again reported in outburst in 2010 June, displaying a similar intensity level as in 2006 (Degenaar et al. 2010c).

Within the disc instability model, we can understand the observed behaviour if in 2006 only part of the accretion disc became ionized, while the 2007–2008 outburst drained a larger part of (or maybe the full) accretion disc (see, e.g., King & Ritter 1998; Lasota 2001). This picture might also provide an explanation for the
fact that the 2006 outburst was fainter than the one observed in 2007–2008, since
the mass-accretion rate (and thus the accretion luminosity) is expected to scale with
the size of the hot ionized zone of the accretion disc (see King & Ritter 1998). We
note that the disc instability model for accreting white dwarfs predicts alternating
sequences of outbursts with different duration and brightness, consistent with obser-
vations of dwarf novae eruptions (e.g., Cannizzo 1993; Lasota 2001). While driven
by the same underlying mechanism, it is thought that in LMXBs the stability prop-
erties are strongly influenced by irradiation of the accretion disc (King & Ritter 1998;
Lasota 2001). As a consequence, LMXBs are expected to consume a larger part of
the accretion disc during outbursts, which are therefore longer and less frequent than
observed for dwarf novae (King & Ritter 1998; Lasota 2001).

Recurrence time of GRS 1741–2853

Despite the different duration and average flux, the fluence of the 2009 outburst of
GRS 1741–2853 is comparable to the 2007 outburst fluence of $1 \times 10^{-3}$ erg cm$^{-2}$
(see Table 6.2). The two outbursts are separated by an epoch of $\sim 2.5$ year. The
total mass accreted during the 2007 outburst can be estimated as $7 \times 10^{-11}$ M$_\odot$
(for $t_{\text{ob}} > 13$ weeks and $\langle \dot{M}\rangle_{\text{ob}} \sim 3 \times 10^{-10}$ M$_\odot$ yr$^{-1}$). For the 2009 outburst we
obtain a comparable value of $4 \times 10^{-11}$ M$_\odot$ ($t_{\text{ob}} \sim 4 – 5$ weeks and $\langle \dot{M}\rangle_{\text{ob}} \sim
5 \times 10^{-10}$ M$_\odot$ yr$^{-1}$).

In 2005, GRS 1741–2853 also underwent an accretion outburst that endured for
several weeks. The rise of this outburst was captured by Integral in 2005 early-April
(Kuulkers et al. 2007c), while Chandra observations indicated that the source was
fading in 2005 early-July (Wijnands et al. 2006a). This suggests an outburst duration
of $\sim 13$ weeks. Assuming an average 2–10 keV flux of $\sim 1 \times 10^{-10}$ erg cm$^{-2}$ s$^{-1}$
as inferred from Chandra observations performed in 2005 June; Wijnands et al.
2006a), we can assess that the 2005 outburst had a 2–10 keV fluence of approximately
$8 \times 10^{-4}$ erg cm$^{-2}$. This is comparable to the two large outbursts occurring in
2007 and 2009 (see Table 6.2). The time between the 2005 and the 2007 outburst is
nearly 2 years. The total mass accreted during the 2005 outburst can be estimated as
$5 \times 10^{-11}$ M$_\odot$ (assuming $t_{\text{ob}} \sim 13$ weeks and $\langle \dot{M}\rangle_{\text{ob}} \sim 2 \times 10^{-10}$ M$_\odot$ yr$^{-1}$). This is
very similar to the values estimated above for the 2007 and 2009 outbursts.

Based on the three outbursts observed for GRS 1741–2853 in the past 5 years
(2005, 2007 and 2009, neglecting the weak and short outburst captured by Swift
in 2006) we can infer that the system has typical outburst duration on the order of
$\sim 10$ weeks. The detection history in the past decade (see Trap et al. 2009, for an
overview), suggests a recurrence time of roughly $\sim 2$ years. This implies a duty cycle
of $\sim 10\%$ and the average accretion rate during outburst appears to be typically a few
times $10^{-10}$ M$_\odot$ yr$^{-1}$.
XMM J174457–2850.3: a wind-fed system?

As discussed in Section 6.3.4, the unclassified transient X-ray source XMM J174457–2850.3 has a quiescent level of \( L_X \sim 10^{32} \text{ erg s}^{-1} \), while the observed maximum luminosity is \( \sim 10^{36} \text{ erg s}^{-1} \) (2–10 keV). The 2008 Swift/XRT observations of the GC show that the bright stages of this source might only last for a few days, while XMM J174457–2850.3 is often found at levels intermediate between quiescence and full outburst, at a 2–10 keV luminosity of \( \sim 10^{33–34} \text{ erg s}^{-1} \). Such behaviour is difficult to understand within the framework of accretion disc instabilities in LMXBs. Instead, wind accretion might provide a more natural explanation.

The activity displayed by XMM J174457–2850.3 is in some ways reminiscent of the behaviour observed from SFXTs, which harbour neutron stars accreting from the stellar wind of a supergiant O/B companion (e.g., Negueruela et al. 2006). These systems undergo sporadic X-ray flares lasting only a few hours to days and reaching up to 2–10 keV luminosities of \( \sim 10^{36–37} \) (e.g., Sidoli 2009). They seem to reside in their quiescent states (\( L_X \sim 10^{32} \text{ erg s}^{-1} \)) only occasionally, and instead linger the majority of their time at levels of \( \sim 10^{33–34} \text{ erg s}^{-1} \) displaying X-ray spectra that are well fit by a powerlaw model with a photon index in the range 1–2 (2–10 keV, e.g., Sidoli et al. 2008). Slow (i.e., a few seconds to minutes) pulsations have been detected from a few of these systems (e.g., Sidoli 2009). An HMXB configuration would be consistent with the possible detection of 5.25 s (0.19 Hz) pulsations from XMM J174457–2850.3 in XMM-Newton observations (Sakano et al. 2005). However, since the data analysis was limited by both statistics and exposure, the reliability of the coherent signal was considered highly uncertain by these authors and this result therefore needs to be verified.

Laycock et al. (2005) report on \( I \)-band images of the field around XMM J174457–2850.3, obtained during an X-ray outburst in 2005 early-June. Using the IMACS imaging spectrograph mounted at the Magellan-Baade telescope, these authors detect an optical source with \( I = 22.04 \pm 0.1 \) mag and \( R - I = 1.95 \pm 0.2 \), a low extinction (\( A_V \sim 7 \) mag) and no variability. However, this object is located \( \sim 3'' \) NE from the Chandra coordinates of XMM J174457–2850.3, lying outside the 1.5'' positional uncertainty (Wijnands et al. 2006a), and is therefore likely not related. This implies that the optical counterpart of XMM J174457–2850.3 has a magnitude \( I > 25.6 \) mag (3\( \sigma \) upper limit; Laycock et al. 2005). Finding an optical counterpart is hampered by the large extinction in the direction of the source. Using the relation of Predehl & Schmitt (1995), a hydrogen column of \( N_H \sim 7.5 \times 10^{22} \text{ cm}^{-2} \) (as inferred from fitting X-ray spectral data; see Section 6.3.4) would translate into a visual extinction of \( A_V \sim 42 \) mag. Since the extinction is much lower at longer wavelengths, it might be more fruitful to search for a counterpart in the infrared.

A recent study by Mauerhan et al. (2009) did not reveal any infrared objects as-
sociated with XMM J174457–2850.3, up to a limiting magnitude of $K_s \lesssim 15.6$ mag. The extinction in the $K_s$ band can be estimated as $A_{K_s} = 0.062 \times A_V \sim 2.6$ mag (Nishiyama et al. 2008). Using the tables of Drilling & Landolt (2000) and Tokunaga (2000) suggests that the survey of Mauerhan et al. (2009) should have enabled the detection of an O/B supergiant ($K_s \sim 11$ mag), as well as a main sequence star with spectral type earlier than B3V. Since most known HMXBs have donor stars with spectral types from O9V–B2V (Negueruela 1998), XMM J174457–2850.3 is not likely to be an HMXB unless the source is more distant than 8 kpc. Its behaviour therefore remains puzzling.

Another possibility to explore is whether this source could be an LMXB in which a neutron star is accreting from the wind of an M-gaint companion. Currently, only 8 of such symbiotic X-ray binaries have been identified (e.g., Masetti et al. 2007; Nespoli et al. 2010). All of these systems show both long- and short-term X-ray variability and are characterised by 2–10 keV luminosities ranging between $\sim 10^{32–35}$ erg s$^{-1}$, although one object shows more intense X-ray emission of $L_X \sim 10^{36–37}$ erg s$^{-1}$ (e.g., Masetti et al. 2007). However, for the extinction towards XMM J174457–2850.3 and a distance of 8 kpc, an M-type giant would have a magnitude of $K_s \sim 11–13$ mag (Drilling & Landolt 2000; Tokunaga 2000). The lack of a counterpart with $K_s \lesssim 15.6$ mag (Mauerhan et al. 2009) therefore renders this scenario unlikely as well unless the source is located at a larger distance than 8 kpc.

### 6.4.2 Mass-accretion rates

Amongst the different transients that are detected during the Swift/XRT monitoring observations of the GC there are two LMXBs (AX J1745.6–2901 and GRS 1741–2853), whereas the others remain unclassified. However, the energies involved in their outburst phenomena make it likely that these harbour accreting neutron stars or black holes. Recently, Mauerhan et al. (2009) searched for near-infrared counterparts to X-ray sources located towards the GC. Their catalogue reveals no counterparts for any of the unclassified transients detected during the Swift campaign, with a limiting magnitude of $K_s \lesssim 15.6$ mag. This suggests that these systems are likely transient LMXBs rather than HMXBs (Muno et al. 2005b; Mauerhan et al. 2009). It is therefore interesting to estimate the mean accretion rate during the outbursts of these systems, $\langle \dot{M} \rangle_{ob}$, from which we can obtain an order of magnitude approximation for the long-term averaged mass-accretion rates, when combined with estimates of their duty cycles.

The time-averaged mass-accretion rate, $\langle \dot{M} \rangle_{long}$, is an important parameter for binary evolution models that attempt to explain the nature of low-luminosity LMXBs (e.g., King & Wijnands 2006). We refer to Degenaar & Wijnands (2009) for the details of such calculations and the associated caveats. Here, we only calculate the
Table 6.2: Overview of the outburst properties and estimated (time-averaged) mass-accretion rates.

<table>
<thead>
<tr>
<th>Source name</th>
<th>Year</th>
<th>$t_{ob}$</th>
<th>$\tilde{F}$</th>
<th>Duty cycle</th>
<th>$\langle \dot{M}_{ob} \rangle$</th>
<th>$\langle \dot{M}_{long} \rangle$</th>
</tr>
</thead>
<tbody>
<tr>
<td>AX J1745.6–2901</td>
<td>2007–2008</td>
<td>&gt; 80</td>
<td>$&gt; 7 \times 10^{-3}$</td>
<td>10–30%</td>
<td>$\sim 3 \times 10^{-10}$</td>
<td>$\sim (3–8) \times 10^{-11}$</td>
</tr>
<tr>
<td></td>
<td>2006</td>
<td>&gt; 16</td>
<td>$\geq 5 \times 10^{-4}$</td>
<td>10–30%</td>
<td>$\sim 1 \times 10^{-10}$</td>
<td>$\sim (3–8) \times 10^{-11}$</td>
</tr>
<tr>
<td>CXO GC J174535.5–290124</td>
<td>2008</td>
<td>&gt; 8</td>
<td>$\geq 7 \times 10^{-6}$</td>
<td>20–50%</td>
<td>$\sim 3 \times 10^{-12}$</td>
<td>$\sim (7–14) \times 10^{-13}$</td>
</tr>
<tr>
<td></td>
<td>2006</td>
<td>&gt; 12</td>
<td>$\geq 2 \times 10^{-5}$</td>
<td>20–50%</td>
<td>$\sim 4 \times 10^{-12}$</td>
<td>$\sim (7–14) \times 10^{-13}$</td>
</tr>
<tr>
<td>GRS 1741–2853</td>
<td>2009</td>
<td>4–5</td>
<td>$\sim 8 \times 10^{-4}$</td>
<td>5–15%</td>
<td>$\sim 5 \times 10^{-10}$</td>
<td>$\sim (2–6) \times 10^{-11}$</td>
</tr>
<tr>
<td></td>
<td>2007</td>
<td>&gt; 13</td>
<td>$\geq 1 \times 10^{-3}$</td>
<td>5–15%</td>
<td>$\sim 3 \times 10^{-10}$</td>
<td>$\sim (2–6) \times 10^{-11}$</td>
</tr>
<tr>
<td></td>
<td>2006</td>
<td>&lt; 1</td>
<td>$\leq 3 \times 10^{-6}$</td>
<td>5–15%</td>
<td>$\sim 8 \times 10^{-12}$</td>
<td>$\sim (2–6) \times 10^{-11}$</td>
</tr>
<tr>
<td>XMM J174457–2850.3</td>
<td>2009</td>
<td>&lt; 2</td>
<td>$\leq 3 \times 10^{-5}$</td>
<td>5–50%</td>
<td>$\sim 4 \times 10^{-11}$</td>
<td>$\sim (1–10) \times 10^{-12}$</td>
</tr>
<tr>
<td></td>
<td>2008</td>
<td>1–7</td>
<td>$\sim (2–10) \times 10^{-5}$</td>
<td>5–50%</td>
<td>$\sim 6 \times 10^{-11}$</td>
<td>$\sim (1–10) \times 10^{-12}$</td>
</tr>
<tr>
<td></td>
<td>2008-low</td>
<td>&gt; 16</td>
<td>$\geq 3 \times 10^{-5}$</td>
<td>5–50%</td>
<td>$\sim 2 \times 10^{-12}$</td>
<td>$\sim (1–10) \times 10^{-12}$</td>
</tr>
<tr>
<td></td>
<td>2007</td>
<td>&lt; 12</td>
<td>$\leq 4 \times 10^{-6}$</td>
<td>5–50%</td>
<td>$\sim 1 \times 10^{-12}$</td>
<td>$\sim (1–10) \times 10^{-12}$</td>
</tr>
<tr>
<td>CXO GC J174538.0–290022</td>
<td>2009</td>
<td>30–52</td>
<td>$\sim (9–20) \times 10^{-5}$</td>
<td>5–20%</td>
<td>$\sim 1 \times 10^{-11}$</td>
<td>$\sim (5–20) \times 10^{-13}$</td>
</tr>
<tr>
<td>CXO GC J174540.0–290005</td>
<td>2006</td>
<td>2</td>
<td>$\sim 1 \times 10^{-5}$</td>
<td>1–5%</td>
<td>$\sim 2 \times 10^{-11}$</td>
<td>$\sim (3–13) \times 10^{-13}$</td>
</tr>
<tr>
<td>Swift J174537.3–290347</td>
<td>2006</td>
<td>2</td>
<td>$\sim 8 \times 10^{-6}$</td>
<td>$\leq 5%$</td>
<td>$\sim 2 \times 10^{-11}$</td>
<td>$\leq 6 \times 10^{-13}$</td>
</tr>
<tr>
<td>Swift J174622.1–290634</td>
<td>2006</td>
<td>5</td>
<td>$\sim 5 \times 10^{-6}$</td>
<td>$\leq 14%$</td>
<td>$\sim 3 \times 10^{-12}$</td>
<td>$\leq 4 \times 10^{-13}$</td>
</tr>
</tbody>
</table>

Note. – The outburst duration, $t_{ob}$, is expressed in weeks. $\tilde{F}$ represents the fluence of the outburst in units of erg cm$^{-2}$ in the 2–10 keV energy band. $\langle \dot{M}_{ob} \rangle$ is the estimated average accretion rate during outburst (M$\odot$ yr$^{-1}$) assuming a neutron star primary with $M = 1.4$ M$\odot$ and $R = 10$ km. The estimated time-averaged mass-accretion rate is given by $\langle \dot{M}_{long} \rangle$. Note that only AX J1745.6–2901 and GRS 1741–2853 are confirmed neutron star X-ray binaries, the other six sources have an unknown nature.

(time-averaged) mass-accretion rates assuming a neutron star primary with $M_{NS} = 1.4$ M$\odot$ and $R_{NS} = 10$ km. These results are listed in Table 6.2. In case of a black hole accretor with $M_{BH} = 10$ M$\odot$ and $R_{BH} = 30$ km, the values given in this table can be multiplied with a factor $\sim 0.4$, although one should bear in mind the caveats discussed in Degenaar & Wijnands (2009).

The duty cycles of AX J1745.6–2901 and GRS 1741–2853 have been estimated in Sections 6.4.1 and 6.4.1, respectively. For a discussion on the outburst and qui-
escent time scales of CXOGC J174535.5–290124 and XMM J174457–2850.3 we refer to Degenaar & Wijnands (2009), since the new 2008–2009 data leaves those estimates unaltered. As mentioned in Section 6.4, the Swift monitoring observations detected activity of three transients in 2006 (Degenaar & Wijnands 2009), that did not recur in 2008–2009. Since Swift J174622.1–290634 was in FOV only during a small number of pointings, we cannot refine the time-averaged mass-accretion rate for this source. However, for CXOGC J174540.0–290005 and Swift J174553.7–290347, we can put further constraints on the time that these systems spend in quiescence. In 2008, daily observations were carried out for 36 consecutive weeks, which can thus be used as a lower limit on the quiescent time scale of the two transients. Both CXOGC J174540.0–290005 and Swift J174553.7–290347 exhibited an outburst with a duration of two weeks in 2006. This new constraint then puts their duty cycles at ≲ 5%. Based on the 2006–2007 data set, duty cycles of ≲ 6% and ≲ 8% were estimated for CXOGC J174540.0–290005 and Swift J174553.7–290347, respectively (Degenaar & Wijnands 2009). Since the former was also active in 2003 (Muno et al. 2005b), the lower limit on its duty cycle is ≳ 1% (Degenaar & Wijnands 2009).

CXOGC J174538.0–290022 was detected for the first time during the Swift/XRT observations performed in 2009. The source was observed with a peak outburst luminosity of ∼ 2 × 10^{35} \text{ erg s}^{-1}. Apart from the 2009 activity, CXOGC J174538.0–290022 has been detected with a luminosity exceeding 1 × 10^{34} \text{ erg s}^{-1} only once before, in 1999 September with Chandra (Muno et al. 2005b). This implies that the quiescent time scale of this source is less than 10 years. On the other hand, the source was not found active throughout the 2006–2008 Swift/XRT monitoring campaign. During those years, nearly daily observations were carried out, only interrupted for 17 weeks between 2006 November and 2007 March, for 15 weeks in the epoch 2007 November–2008 February (both due to Sun-angle constraints), and for 6 weeks between 2007 August 11–September 26 (due to a safe-hold event; Gehrels 2007). If an outburst duration of 30–52 weeks is typical for this source, we can thus put a lower limit on the quiescent time scale of ∼ 2.7 years (139 weeks), although shorter outbursts might have been missed. The duty cycle of this source is then roughly between ∼ 5 – 20%, which results in a time-averaged mass-accretion rate of $\langle \dot{M} \rangle_{\text{long}} \sim (5 – 20) \times 10^{-13} M_\odot \text{ yr}^{-1}$ (see Table 6.2). Despite the apparent long outburst duration, the estimated time-averaged accretion rate is amongst the lowest of the transients detected in the Swift/XRT monitoring campaign of the GC.

It can be seen from Table 6.2 that the two confirmed neutron star LMXBs AX J1745.6–2901 and GRS 1741–2853 have estimated time-averaged mass-accretion rates of a few times $10^{-11} M_\odot \text{ yr}^{-1}$, which is not extraordinary low compared to other LMXBs. XMM J174457–2850.3 is also amongst the brightest transients detected during the Swift monitoring observations ($L^\text{peak}_X \sim 10^{36} \text{ erg s}^{-1}$) and this sys-
tem appears to recur quite often. This results in a relatively high time-averaged mass-accretion rate \( \left( 10^{-12} - 10^{-11} \, M_\odot \, yr^{-1} \right) \) compared to the other five transients listed in Table 6.2, which have lower outburst luminosities and lower estimated rates of \( \langle \dot{M} \rangle_{\text{long}} \lesssim 2 \times 10^{-12} \, M_\odot \, yr^{-1} \).

As mentioned above, the time-averaged mass-accretion rate is an important parameter for binary evolution models. King & Wijnands (2006) construct a theoretical toy model exploring the evolution of LMXBs at low accretion luminosities. The estimates of these authors show that if objects like CXOGC J174535.5–290124, CXOGC J174538.0–290022, CXOGC J174540.0–290005, Swift J174553.7–290347 and Swift J174622.1–290634 are indeed X-ray binaries, their time-averaged mass-accretion rates suggests that the mass-donors are likely very low-mass or hydrogen-depleted stars. However, further refinement of their duty cycles and outburst energetics, as well as detailed evolutionary calculations, are required to grasp the nature of these peculiar objects.

### 6.4.3 Summary of the campaign 2006–2009

Starting in 2006 February and extending into 2009, the Swift/XRT monitoring campaign of the GC detected activity of 8 different transients in total, from which 14 distinct outbursts were observed. All sources have experienced outbursts with peak 2–10 keV luminosities \( L_X^{\text{peak}} \lesssim 10^{36} \, \text{erg s}^{-1} \), although the two neutron star LMXBs AX J1745.6–2901 and GRS 1741–2853 both displayed brighter outbursts as well \( (L_X^{\text{peak}} \sim 10^{36–37} \, \text{erg s}^{-1}) \). Two of the eight transients are newly discovered sources, which were both active in 2006 (Swift J174553.7–290347 and Swift J174622.1–290634; Degenaar & Wijnands 2009). Four of the eight transients were observed to recur over the 4-year time span of this campaign (see Table 6.2) and have relatively short recurrence times. These transients show a different peak flux, duration and lightcurve morphology from outburst to outburst, which is also seen in brighter X-ray transients (Chen et al. 1997).

Currently, there are 13 X-ray transients exhibiting 2–10 keV peak luminosities \( \gtrsim 10^{34} \, \text{erg s}^{-1} \) known in the region covered by the Swift/XRT monitoring observations.\(^4\) Out of these 13 transients, only 1A 1742–289 becomes brighter than \( L_X > 10^{37} \, \text{erg s}^{-1} \) (2–10 keV; see Wijnands et al. 2006a, and references therein), while the remaining 12 undergo low-luminosity outbursts. The three sources AX J1745.6–2901, GRS 1741–2853 and XMM J174457–2850.3 are the brightest amongst these and have 2–10 keV peak luminosities of \( 10^{36–37} \, \text{erg s}^{-1} \), but the other 9 transients

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\(^4\)The Swift monitoring observations cover all sources listed in table A.1 of Wijnands et al. (2006a) that are located within \( \sim 14' \) distance from Sgr A*. In addition to the 11 objects from their list, two new transients were discovered by Swift in 2006 (Swift J174553.7–290347 and Swift J174622.1–290634; Degenaar & Wijnands 2009).
have never been observed with luminosities exceeding $10^{36}$ erg s$^{-1}$. From the 12 low-luminosity transients, 7 were observed to recur in the past decade and thus have relatively short recurrence times. The remaining 5 objects (CXOGC J174540.0–290031, CXOGC J174554.3–285454, XMM J174544–2913.0, Swift J174553.7–290347 and Swift J174622.1–290634) were seen active only once and thus seem to recur less often.

Despite the fact that > 250 ks of new Swift data was obtained, spread over almost daily observations in 2008 and 2009, no new transients were found. Muno et al. (2009) suggested that given the extensive monitoring of the GC in the past years, all X-ray binaries that are located in that region and recur on a time scale of a decade have been identified by now. The galactic population of X-ray binaries (both LMXBs and HMXBs) is expected to encompass ~ 2000 objects (e.g., Verbunt & van den Heuvel 1995). The region around Sgr A* that has been monitored by Chandra, XMM-Newton and Swift in the past decade covers ~ 1% of the stellar mass in the galactic disc (Pfahl et al. 2002). In this region, ~ 20 likely X-ray binaries have been identified (Muno et al. 2009). Most of these are transient sources and strikingly, the majority have very low 2–10 keV peak luminosities of $\lesssim 10^{36}$ erg s$^{-1}$ (Muno et al. 2005b; Wijnands et al. 2006a; Degenaar & Wijnands 2009).

The number of likely X-ray binaries that have been identified in the vicinity of Sgr A* is thus consistent with that expected from population synthesis models. However, the GC has been monitored with instruments sensitive enough to detect low-luminosity transients only in the past decade and several of the currently known systems appear to have relatively short recurrence times compared to brighter X-ray transients (e.g., Chen et al. 1997). Continued monitoring of the GC is therefore important to search for transient outbursts from new systems to better constrain the number of X-ray binaries located near Sgr A*, and to gain more insight into the duty cycles of known systems.

Acknowledgments
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Chandra/XMM-Newton monitoring campaign of the Galactic centre: analysing the X-ray transients

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Abstract – We report on the results from a 4-year long X-ray monitoring campaign of the central 1.2 square degree of our Galaxy, performed with Chandra and XMM-Newton between 2005 and 2008. Our study focusses on the properties of transient X-ray sources located in the surveyed region that have 2–10 keV peak luminosities exceeding $\sim 10^{34}$ erg s$^{-1}$ for an assumed distance of 8 kpc. There are 16 previously known X-ray transients within field of view of our campaign, 8 of which were detected in outburst during our observations: the transient neutron star low-mass X-ray binaries GRS 1741–2853, AX J1745.6–2901, SAX J1747.0–2853, KS 1741–293 (all four X-ray bursters) and GRO J1744–28 (a 2.1 Hz X-ray pulsar), as well as the unclassified X-ray transients XMM J174457–2850.3, CXOGC J174535.5–290124 and CXOGC J174541.0–290014. Our campaign detected type-I X-ray bursts from AX J1745.6–2901 and SAX J1747.0–2853. For the latter, we observed two bursts with similar durations and peak intensities, that were separated by a time interval of only 3.8 minutes. We find a previous unknown X-ray source in our XMM-Newton observations, which we designate XMMU J174554.1–291542. This object emits most of its photons above 2 keV and appears to be persistent at a luminosity of $\sim 10^{34}$ erg s$^{-1}$ (assuming a distance of 8 kpc), although it exhibits strong spectral variability on a time scale of months.
7 The Chandra/XMM-Newton monitoring campaign of the Galactic centre

7.1 Introduction

The region around Sgr A*, the dynamical centre of our Galaxy, has been observed at various spatial scales and in different energy bands by many past and present X-ray missions. At early times, dedicated monitoring campaigns using Einstein (Watson et al. 1981), Granat (Churazov et al. 1994; Pavlinsky et al. 1994), ROSAT (Sidoli et al. 2001a), ASCA (Sakano et al. 2002) and BeppoSAX (Sidoli et al. 1999; in’t Zand et al. 2004) have led to the discovery of several X-ray point sources located within the central degrees of our Galaxy. More recently, an intensive monitoring campaign carried out with Chandra between 1999 and 2006 has resolved thousands of distinct X-ray sources in a field of 2° × 0.8° around the Galactic centre (GC; Wang et al. 2002; Baganoﬀ et al. 2003; Muno et al. 2003b, 2004, 2006, 2009). Furthermore, starting in 2006 the inner ~ 25′ × 25′ around Sgr A* has been monitored on an almost daily basis with Swift (Kennea & The Swift/XRT team 2006; Degenaar & Wijnands 2009, 2010), whereas a region subtending many degrees around Sgr A* has been regularly scanned by Integral starting in 2005 (Kuulkers et al. 2007c) and by RXTE since 1999 (Swank & Markwardt 2001).

The plethora of X-ray sources found in the direction of the innermost parts of our Galaxy encompasses a variety of objects (e.g., Muno et al. 2004). The brightest point sources have 2–10 keV peak luminosities of ~ 10^{36–39} erg s^{-1} and can be identiﬁed with neutron stars or black holes accreting matter from a companion star. Based on the nature of the companion, these systems are classiﬁed as high-mass X-ray binaries (HMXBs; M_{donor} ≳ 10 M_{\odot}) or low-mass X-ray binaries (LMXBs; M_{donor} ≲ 1 M_{\odot}). The presence of a neutron star is evidenced by the detection of thermonuclear X-ray bursts (e.g., Strohmayer & Bildsten 2006) or X-ray pulsations (e.g., Psaltis 2006). Many X-ray binaries are transient and are bright only during short (weeks to months) episodes, while the majority of their time is spent in a quiescent state during which the X-ray luminosity is typically at least two orders of magnitude lower than during outburst. The orders of magnitude variability displayed by these systems is thought to be due to large changes in the mass-accretion rate onto the compact primary.

Whereas previous X-ray missions detected primarily luminous X-ray binaries, deep X-ray observations with Chandra and XMM-Newton have provided views of such systems in their quiescent states (L_X ≤ 10^{33} erg s^{-1}, e.g., Rutledge et al. 2000; Wijnands & Wang 2002; Muno et al. 2003a). However, it has also become clear that some X-ray binaries undergo episodes of low level accretion activity, giving rise to X-ray luminosities intermediate between quiescence and their bright outbursts (e.g., Wijnands et al. 2002c; Degenaar & Wijnands 2009). Furthermore, repeated observations of the region around Sgr A* with Chandra, XMM-Newton and Swift have revealed a population of transient X-ray sources that have 2–10 keV peak luminosities of only ~ 10^{34–36} erg s^{-1} and have never been observed in a brighter state (e.g.,
7.1 Introduction

Muno et al. 2005b; Sakano et al. 2005; Porquet et al. 2005b; Degenaar & Wijnands 2009). These systems can likely be identified with X-ray binaries in which the compact object accretes at a very low rate from its companion star (e.g., Pfahl et al. 2002; Belczynski & Taam 2004; Muno et al. 2005b). Earlier X-ray missions already provided a glimpse of low-luminosity X-ray transients (Sunyaev 1990; in ’t Zand et al. 1991; Maeda et al. 1996), but the current generation of instruments exploiting X-ray imaging have significantly improved our understanding of such objects.

Observations of X-ray binaries accreting at low X-ray luminosities can address several issues related to stellar and binary evolution, as well as accretion flows at low rates. For example, constraining the number and nature of low-luminosity X-ray transients allows us to gain more insight into the statistics of different source populations. This can serve as an important calibration point for population synthesis models (e.g., Pfahl et al. 2002; Belczynski & Taam 2004). Furthermore, the mass-accretion rate averaged over thousands of years, \( \langle \dot{M} \rangle_{\text{long}} \), is an important parameter for understanding the evolution of LMXBs. First studies have shown that the low-luminosity X-ray sources might pose an interesting challenge for binary evolution. If the time-averaged mass-accretion rate is not significantly below \( \sim 10^{-13} \, M_\odot \, \text{yr}^{-1} \), these systems can potentially be explained as very old LMXBs that have spent most of the age of the Galaxy reducing their companion masses to \( \sim 0.01 \, M_\odot \) (King & Wijnands 2006). However, much lower time-averaged mass-accretion rates put tight constraints on the possible evolutionary paths and might require unusual binary compositions, such as neutron stars accreting from hydrogen-depleted or planetary companions (King & Wijnands 2006). Thus, dedicated surveys aiming to search for very faint X-ray transients have the potential to unveil rare types of accreting compact objects. Repeated non-detections of these systems drives down their time-averaged mass-accretion rates and can therefore be as interesting as actual detections.

The luminosity range of \( \sim 10^{33-36} \, \text{erg s}^{-1} \) constitutes a relatively poor explored regime of accretion. This is in part due to the fact that transients usually spend only a short time in this regime, when transitioning from outburst to quiescence or vice versa. Studying the properties of low-luminosity X-ray sources improves the prospects for better understanding the processes underlying their transient behaviour. The outburst profiles, duration of the quiescent and active intervals, as well as the spectral and timing properties should all serve as a diagnostic of these processes (see e.g., King 2006; van der Klis 2006, for reviews). In addition, thermonuclear X-ray bursts observed from systems accreting at low rates have provided important new insight into the physics of nuclear burning on the surface of neutron stars (e.g., Cornelisse et al. 2002; in ’t Zand et al. 2005a; Cooper & Narayan 2007; Peng et al. 2007; Degenaar et al. 2010a).

In this work, we report on the results from a joint Chandra and XMM-Newton
monitoring campaign covering the region around Sgr A*, carried out between 2005 and 2008. Wijnands et al. (2006a) reported on the initial results of our monitoring observations, discussing the first series of data obtained in June and July 2005. The main goal of this program is to investigate the X-ray properties (below 10 keV) of transient objects that have low 2–10 keV peak luminosities of $\sim 10^{34–36}$ erg s$^{-1}$. Due to the high concentration of X-ray point sources in the inner square degree around Sgr A*, as well as sensitivity limitations, such systems are generally inaccessible to monitoring instruments in orbit (e.g., RXTE, Integral, Swift/BAT). Our Chandra/XMM-Newton campaign aids to refine our understanding of currently known low-luminosity systems (e.g., improve estimates of their duty cycles and time-averaged accretion rates), and search for new transients.

### 7.2 Description of the program

Our choice to monitor the central square degree of our Galaxy was predetermined by the fact that this region is populated by nearly 20 known X-ray transients, several of which undergo subluminous accretion episodes (Muno et al. 2005a; Wijnands et al. 2006a). The wide field of view (FOV; $\sim 30' \times 30'$) and large collective area ($\sim 1100$ cm$^2$ at 1 keV) of XMM-Newton make it an excellent facility for surveying sky regions down to relatively faint flux levels. We use the data obtained with the European Photon Imaging Camera (EPIC), which consists of one PN (Strüder et al. 2001) and two MOS (Turner et al. 2001) detectors that are sensitive in the 0.1–15 keV range and have spectral imaging capabilities. The PN is an array of 12 CCDs ($64 \times 200$ pixels each), while the MOS units consist of an array of 7 CCDs, each consisting of $600 \times 600$ pixels. A micrometeoroid strike damaged one of the CCDs of the MOS1, which is operated with only 6 detectors since (Abbey et al. 2006).

Our XMM-Newton observations are complemented by Chandra pointings, providing high spatial (sub-arcsec) resolution and a very low X-ray background, within an energy band of 0.1–10 keV. We chose the High Resolution Camera (HRC; Kenter et al. 2000) as the prime Chandra instrument for our monitoring observations, because it provides the largest FOV, comparable in size to XMM-Newton ($\sim 30' \times 30'$). The HRC-I is a square micro-channel plate detector (made up of $32768 \times 32768$ pixels) that has an effective area of 225 cm$^2$ at 1 keV and is designed for imaging observations. Because the energy resolution of the HRC is poor, we obtained a few additional pointings with the Advanced CCD Imaging Spectrometer (ACIS; Garmire et al. 2003) to follow-up active transients, thereby obtaining spectral information that aids to further classify the systems and better constrain their outburst properties. The ACIS-I consists of a 4-chip imaging array (each having $1024 \times 1024$ pixels), providing an effective area of 340 cm$^2$ at 1 keV and a FOV of $\sim 16' \times 16'$. 

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7.2 Description of the program

Figure 7.1: Composite X-ray images of our monitoring campaign (2005–2008). The field names of the different pointings are given in boxes. The locations of active transients and persistent and X-ray binaries are indicated by circles. Non-labelled X-ray sources seen in these images can be identified with stars or star clusters. Top left: XMM-Newton/PN mosaic image. Top right: Chandra/HRC-I image. Bottom: HRC-I image magnified to display the inner ∼ 1.5′ around Sgr A*.

Our Chandra/XMM-Newton campaign covers 1.2 square degree around Sgr A*, sub-divided into 7 different pointing directions (named GC-1, GC-2, GC-3, GC-4, GC-5, GC-6 and GC-7; Wijnands et al. 2006a).1 Adjacent pointings were partially overlapped by a few arcminutes (see Figure 7.1). The program comprises 34 Chandra/HRC-I and 35 XMM-Newton/EPIC pointings, carried out in 10 different epochs between 2005 June and 2008 September. An overview of the monitoring observa-

1We note that the naming of the different pointing directions changed during our campaign. The fields that were initially denoted as GC-7, GC-8, GC-9 and GC-10 in the 2005–2006 observations (see Wijnands et al. 2006a) were in 2007–2008 renamed GC-4, GC-5, GC-6 and GC-7, respectively. We adapt the latter indications throughout this work.
The Chandra/XMM-Newton monitoring campaign of the Galactic centre  

...tions is given in Table 7.1. Follow-up Chandra/ACIS-I observations were carried out in 2005 July (1 pointing) and 2007 March–May (a series of 5 pointings), and are listed in Table 7.2. The exposure time of individual observations was typically 5–10 ks. Depending on the exact spectral shape and column density, a 5 ks Chandra/HRC-I pointing can detect sources (near aimpoint) down to \( \sim (3 - 6) \times 10^{33} \left( \frac{D}{8 \text{ kpc}} \right)^2 \text{ erg s}^{-1} \) for column densities of \( (5 - 10) \times 10^{22} \text{ cm}^{-2} \) and photon indices of \( \Gamma = 1.0 - 3.0 \). The XMM-Newton observations are a factor of a few more sensitive.

Our campaign spans a period of 39 months (3.25 year), for a cumulative exposure time of 412.7 ks (168.1 ks with Chandra, 244.6 ks with XMM-Newton). Subsequent pointings are separated by 2–10 months (see Table 7.1), allowing us to investigate the X-ray variability of the detected sources on such time scales. The total exposure time reached in the different pointing directions is \( \sim 46 - 68 \) ks. Mosaic images of the Chandra/HRC-I and XMM-Newton/PN data are shown in Figure 7.1. Apart from diffuse X-ray structures around Sgr A*, these images reveal a number of X-ray point sources (see also Section 7.4). The locations of active transients and persistent X-ray binaries are indicated by circles and the cross-hair in the centre of the images shows the position of the Sgr A* complex. Figure 7.1 also includes a zoomed Chandra/HRC image of the inner \( \sim 1.5' \) around Sgr A*, where three active X-ray transients were detected.

### 7.3 Data analysis

For the present study we are interested in (candidate) transient X-ray binaries. We therefore focus on transient X-ray sources that have a 2–10 keV peak luminosity of \( \geq 1 \times 10^{34} \text{ erg s}^{-1} \) for an assumed distance of 8 kpc, since fainter objects are likely to be cataclysmic variables (Verbunt et al. 1997). We searched for transient sources in our Chandra and XMM-Newton data by comparing images of different epochs with one another. The objects detected in our observations were correlated with the Simbad database to identify the known X-ray sources in our sample based on positional coincidence. Furthermore, we overlaid the positions of sources found in our campaign on an optical image from the Digital Sky Survey (DSS) and a Two Micron All Sky Survey (2MASS) infra-red survey image, to filter out likely foreground objects (e.g., active stars). Spectral information obtained from our XMM-Newton and Chandra/ACIS-I observations also aids to identify transients that are located at or beyond the distance of the GC (\( \sim 8 \) kpc). These sources will appear relatively hard in X-rays, since the soft photons (below \( \sim 2 \) keV) will be strongly absorbed by the interstellar medium (hydrogen column densities of several times \( 10^{22} \text{ cm}^{-2} \) are typical in this region). Softer X-ray sources are likely to be foreground X-ray active stars or cataclysmic variables, located within a few kiloparsecs from the Sun.
### Table 7.1: Log of the monitoring observations.

<table>
<thead>
<tr>
<th>Field</th>
<th>Obs ID</th>
<th>Date</th>
<th>$t_{\text{exp}}$ (ks)</th>
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<td>5.1</td>
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### Table 7.2: Log of Chandra/ACIS-I follow-up pointings.

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To characterise the X-ray spectra and calculate source fluxes, we fitted the obtained spectral data within XSPEC (v. 12.0; Arnaud 1996) to a powerlaw model, modified by interstellar absorption. For the latter we employ the PHABS model with the default XSPEC abundances and cross-sections (Anders & Grevesse 1989; Balucinska-Church & McCammon 1992). Using the tool GRPHAS we grouped the spectra of the brightest sources to contain a minimum number of 20 photons per bin, whereas fainter objects were binned into groups of at least 10 or 5 photons. In case a source was detected during multiple observations, we fitted the spectra simultaneously with the hydrogen column density tied between the individual observations. We converted the deduced unabsorbed 2–10 keV fluxes to luminosities adopting a distance of 8 kpc, unless better distance estimates were available for sources, e.g., inferred from type-I X-ray burst analysis. Finally, we created long-term lightcurves for each transient source detected during our campaign.

The detailed data reduction and analysis procedures for both satellites are discussed in the next sections. For completeness, our analysis includes the Chandra observations performed in 2005 June (HRC) and July (ACIS), that were previously discussed by Wijnands et al. (2006a).

7.3.1 Chandra

The Chandra observations were treated using the CIAO tools (v. 4.2). The ACIS-I observations were carried out in the faint data mode with the nominal frame time of 3.2 s. As an initial step, we reprocessed the HRC and ACIS level-1 data files following the standard data preparation procedures. Each individual pointing was inspected for periods of unusually high background that can arise due to charged particles (causing the background event rate to flare $\gtrsim 3\sigma$ above the mean level). No significant background flares were found during our Chandra observations, so all data was used in further analysis.

To search our Chandra observations for X-ray sources, we employed the WAVDETECT tool with the default 'Mexican Hat' wavelet (Freeman et al. 2002). To avoid finding spurious sources, most often located at the edge of the FOV, we generated an exposure map for each observation, evaluated at an energy of 4 keV (which is the approximate energy at which our observations detect the largest number of photons for X-ray binaries - the objects of our prime interest). For each HRC-I observation, we generated images with a binning of 4, 16 and 32 pixels, and ran the WAVDETECT routine with two different scale parameters (2.0 and 4.0) on each of the separate images. This approach allowed us to cover a range of source sizes, accommodating the variation of the point spread function (PSF) as a function of off-axis angle. Furthermore, we

\[\text{http://cxc.harvard.edu/ciao/guides.}\]
adapt a recommended significance threshold that is the inverse of the total number of pixels in the image (e.g., \(1 \times 10^{-7}\) and \(1 \times 10^{-6}\) for HRC images binned by a factor of 4 and 16, respectively), which corresponds to one expected spurious source per image (Freeman et al. 2002). We compiled a master source list for each observation by combining the objects detected at each image resolution. For the ACIS-I data we employed the wavdetect tool for images that were binned by a factor of 4, using the same scale parameters and detection significance threshold as for the HRC observations. We ran the detection routine separately in the 0.5–2 and 2–10 keV band, to be able to distinguish immediately between soft and harder X-ray sources.

For each detected source we extracted net count rates and lightcurves using the tool dmextract. As such, we employed extraction regions centred on the positions found by the wavdetect routine and containing \(\sim 95\%\) of the source counts. Background events were collected from a source-free region that had a radius three times that of the source region. We inspected the lightcurves to search for features such as thermonuclear X-ray bursts and X-ray flares. For the ACIS-I data, we extracted source and background spectra using psextract. Redistribution matrices (rmf) and ancillary response files (arf) were subsequently generated using the tasks mkacis-rmf and mkarf, respectively. Since the HRC provides poor energy resolution, we converted the HRC-I count rates to 2–10 keV unabsorbed fluxes employing pimms (v. 4.1) and using either the spectral information deduced from our Chandra/ACIS and XMM-Newton observations, or the spectral values reported in literature (see Table 7.3). If a transient source was not detected, we obtained a 2\(\sigma\) Bayesian statistical upper limit on the source count rate using the CIAO tool asprates.

For the two sources AX J1745.6–2901 and GRS 1741–2853 (see Section 7.4), the ACIS data was subject to pile-up, as evidenced by the occurrence of readout streaks on the CCD images. Pile-up is caused when the count rate is so high compared to the CCD readout time, that multiple soft photons are registered as single events with higher energy. In case of pile-up the broad-band count rate is typically underestimated and the spectrum hardens. We attempt to correct for the effect on spectral shape via an iterative approach in which we extracted source photons from annular extraction regions with increasingly large fractions of the core PSF excluded. Once the spectral parameters remained unchanged after increasing the annular radius we assumed that the piled-up inner regions, distorting the spectral shape, were sufficiently excluded. Unlike for XMM-Newton, the Chandra analysis software does not account for using an annular extraction region, i.e., when creating the arf file with the standard CIAO tools it is assumed that the fraction of source counts contained in the extraction region equals 1, which is not the case when an annulus is used. To apply the necessary PSF corrections, we employed the ARFCORR package.\(^3\)

7.3.2 XMM-Newton

In all XMM-Newton observations, the EPIC cameras were operated in full window mode. The observations carried out in 2008 March and September had the thin optical blocking filter selected, whereas the medium filter was used during the other observations. All analysis was performed using the Science Analysis Software (SAS, v. 10.0.0). Starting with the original data files, the MOS and PN data were reprocessed using the tools EMPROC and EPPROC, respectively. The instrument background in both the MOS and PN cameras is highly variable. In order to assess the background conditions in each of the XMM-Newton observations, we extracted the full-field lightcurve for pattern-0 events with energies of $\gtrsim 10$ keV for the MOS, and between 10–12 keV for the PN. This revealed that some of our observations suffered from background flaring. Because the source detection probability is sensitive to the background rate, we excluded such episodes by selecting only data with high-energy count rates below 0.5 counts s$^{-1}$ for the MOS and below 1.0 counts s$^{-1}$ for the PN. Table 7.1 lists the original exposure times, i.e., before such filtering was applied.

Source detection was carried out with the task EDETECT_CHAIN. We search in two different energy bands of 0.5–2.0 and 2.0–12.0 keV for the PN and the MOS2. We did not include the MOS1 for source detection, since one of the CCD units was damaged by a micrometeoroid strike (Abbey et al. 2006). We extracted (exposure corrected) count rates for all objects in our source list using the task EREGIONALYSE, which returns a $2\sigma$ upper limit in case of a non-detection, using the Bayesian statistics of Kraft et al. (1991). We also employed the EREGIONALYSE tool to determine the optimum extraction region (achieving the highest signal to noise ratio) for source lightcurves and spectra. This yielded source regions with a typical enclosed energy fraction of $\sim 85 – 95\%$. For the extraction of background events we used regions with a radius three times larger than that of the source, positioned on a source-free portion of the CCD.

We created background corrected lightcurves for the PN and both MOS cameras using the tools EVSELECT and EPICLCORR. Source and background spectra, as well as the associated rmf and arf files, were generated using the metatask ESPECGET. The MOS and PN spectral data were fitted within XSPEC in the 0.5–10 keV energy range, with all spectral parameters tied between the three EPIC detectors. During our observations, both AX J1745.6–2901 and SAX J1747.0–2853 became bright enough to cause pile-up in the EPIC instruments (see Section 7.4). We used the SAS task EPANPLT to evaluate the level of pile-up in the MOS and PN data, using annular regions of increasing size. Once the observed pattern distribution matched the expected one, we choose that annular size to extract source photons. Furthermore, we selected only pattern-0 events, which are least affected by pile-up.\footnote{http://xmm2.esac.esa.int/docs/documents/CAL-TN-0036-1-0.}
Table 7.3: Spectral parameters and obtained X-ray fluxes for (candidate) transient X-ray binaries.

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<th>(F_{X,\text{abs}})</th>
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<td>1.25 (4185)</td>
<td>115 ± 2</td>
<td>311 ± 8</td>
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<td>2007-05-16</td>
<td>ACIS</td>
<td>GC-2</td>
<td>21.8 ± 0.3</td>
<td>1.6 ± 0.1</td>
<td>1.25 (4185)</td>
<td>61.1 ± 1.7</td>
<td>154 ± 4</td>
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<td>2.0 fix</td>
<td>144 ± 3</td>
<td>400 ± 8</td>
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<td>PN</td>
<td>GC-2</td>
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<td>GC-7</td>
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<td>GC-7</td>
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<td>63.9 ± 0.2</td>
<td>143.4 ± 3.9</td>
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Note.– Quoted errors represent 90% confidence levels. The hydrogen column density is given in units of \(10^{22}\) cm\(^{-2}\) and the absorbed and unabsorbed 2–10 keV model fluxes in units of \(10^{−12}\) erg cm\(^{-2}\) s\(^{-1}\). *Hydrogen column density fixed at the value reported by Degenaar & Wijnands (2009). bFluxes were derived excluding the eclipse and the type-I X-ray burst contained in the data of 2007 April 6 and 2008 May 10, respectively.
### Table 7.3: Continued.

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<th>(\Gamma)</th>
<th>(\chi^2) (d.o.f.)</th>
<th>(F^\text{abs})_X</th>
<th>(F^\text{unabs})_X</th>
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<td>1.07 (159)</td>
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Note:– c Adopted the spectral parameters given by Muno et al. (2004). dParameters from fitting Swift spectral data (see Section 7.4.9).
Figure 7.2: Background corrected X-ray spectra of the (candidate) transient X-ray binaries detected during our monitoring campaign. Some spectra have been rebinned for representation purposes. Note that AX J1742.6–2901 and CXOGC J174541.0–290014 were only detected during Chandra/HRC observations and therefore no spectral information could be deduced from this campaign.
7.4 Results

Each of our *Chandra* and *XMM-Newton* observations reveal about a dozen distinct X-ray sources. Amongst the detected objects are the Arches cluster and Sgr A*, which are both complexes of X-ray point sources combined with diffuse structures. Several point sources detected during our observations could be identified with known stars or had clear DSS/2MASS counterparts, which renders them likely foreground objects. Our observations also detect two persistent X-ray binaries, 1E 1743.1–2843 and 1A 1742–294. The former is an LMXB black hole candidate (e.g., Porquet et al. 2003), whereas 1A 1742–294 is an LMXB harbouring a neutron star, as evidenced by the detection of type-I X-ray bursts (e.g., Pavlinsky et al. 1994). Our monitoring observations caught a total of 6 type-I X-ray bursts from this system in the *Chandra/HRC* observations with IDs 6200 and 9040, as well as in the *XMM-Newton* observations with IDs 0302884401, 0504940601 and 0511001101.

In this work we focus on the properties of the transient (candidate) X-ray binaries detected during our campaign. The results obtained for individual sources are reported in the following sections, while summarised in Table 7.3. Figure 7.2 displays the X-ray spectra obtained for the active transients. The evolution of their 2–10 keV X-ray luminosities during our campaign is plotted in Figure 7.6 at the end of this chapter. All fluxes reported in this work are given for the 2–10 keV energy band and luminosities were calculated assuming a distance of 8 kpc, unless stated otherwise. Some of the detected transients were within FOV of two different pointing directions (e.g., the source locations of GRS 1741–2853 and XMM J174457–2850.3 are covered in both the GC-2 and GC-4 fields). In these cases we report only the information extracted from the observations in which the source is closest to aimpoint.

As mentioned in Section 7.1, the inner region around Sgr A* (field GC-2 in our campaign), has been covered by the X-ray telescope (XRT; Burrows et al. 2005)
aboard the Swift satellite, beginning in 2006 (Kennea & The Swift/XRT team 2006; Degenaar & Wijnands 2009, 2010). The quasi-daily Swift observations thus provide a partial overlap with our campaign. For sources located in this region we will therefore compare reports on the Swift data with results from our Chandra/XMM-Newton observations.

7.4.1 GRS 1741–2853

On two different epochs, our Chandra observations detect activity of a transient X-ray source consistent with the position of GRS 1741–2853 (Muno et al. 2003a), a neutron star LMXB discovered by the Granat observatory in 1990 (Sunyaev 1990). This source is known to display type-I X-ray bursts (e.g., Cocchi et al. 1999), from which a distance of 7.2 kpc can be inferred (Trap et al. 2009). GRS 1741–2853 has been detected in an active state many times since its discovery, by different X-ray satellites (see Trap et al. 2009, for an historical overview). The source typically reaches a 2–10 keV peak luminosity of \( \sim 10^{36-37} \left( \frac{D}{7.2 \text{ kpc}} \right)^2 \text{ erg s}^{-1} \) during outbursts that endure for a few weeks (e.g., Degenaar & Wijnands 2010).

GRS 1741–2853 is first detected in outburst during the HRC observations performed on 2005 June 5 and is also seen in the follow-up ACIS pointing obtained on 2005 July 1 (Wijnands et al. 2006a). Over the one month time span separating these two observations, the source intensity decreased by a factor \( \sim 4 \) (see Table 7.3), from \( L_X \sim 6 \times 10^{35} \) to \( 1.5 \times 10^{35} \left( \frac{D}{7.2 \text{ kpc}} \right)^2 \text{ erg s}^{-1} \), which suggests that the activity was ceasing. The rise of this outburst was caught by Integral bulge scan monitoring observations in 2005 early-April (Kuulkers et al. 2007c). If the decrease in flux signalled by the Chandra data is indeed due to a transition towards quiescence, this constrains the duration of the 2005 outburst to be \( \sim 13 \) weeks.

This source is again found active during Chandra observations carried out on 2007 March 12, at which time it was bright enough to cause pile-up of the ACIS instrument. We therefore extracted the source spectrum using a 10–40″ annulus, avoiding the inner piled-up part of the source PSF (see Section 7.3.2). The inferred source luminosity for this observation is \( \sim 2 \times 10^{35} \left( \frac{D}{7.2 \text{ kpc}} \right)^2 \text{ erg s}^{-1} \). During the subsequent observation performed on 2007 April 6, GRS 1741–2853 had nearly faded one order of magnitude (see Table 7.3), whereas the source was not detected on April 18. The upper limit on the 2–10 keV luminosity inferred from this observation is \( \lesssim 2.6 \times 10^{32} \text{ erg s}^{-1} \), which indicates that the source had returned to the quiescent state (see Figure 7.6). The 2007 outburst of GRS 1741–2853 was covered by different satellites (Kuulkers et al. 2007a; Wijnands et al. 2007; Muno et al. 2007b; Porquet et al. 2007). The Swift/XRT observations of the GC detected the source with a peak luminosity of \( 1.5 \times 10^{36} \left( \frac{D}{7.2 \text{ kpc}} \right)^2 \text{ erg s}^{-1} \) and constrain the outburst duration to be \( \gtrsim 13 \) weeks (Degenaar & Wijnands 2010).
A joint fit to the ACIS spectral data obtained in 2005 and 2007 yields an hydrogen column density of \((11.4 \pm 1.1) \times 10^{22} \text{ cm}^{-2}\) and photon indices of \(\Gamma \sim 1.5 - 2.0\) (see Table 7.3). These values are comparable to those found for previous outbursts of GRS 1741–2853 (Muno et al. 2003a; Trap et al. 2009). The count rate detected during the 2005 June Chandra/HRC pointing, and upper limits inferred from observations during which the source was not detected, were converted to 2–10 keV unabsorbed fluxes using a powerlaw index of \(\Gamma = 2.0\) and the best-fit hydrogen column density of \(N_H = 11.4 \times 10^{22} \text{ cm}^{-2}\). Figure 7.2 displays the three different Chandra/ACIS spectra obtained for GRS 1741–2853.

Apart from the two mayor outbursts observed in 2005 and 2007, Swift/XRT monitoring observations of the GC exposed a weak, short outburst from GRS 1741–2853 between September 14–20, during which the source did not become brighter than \(L_X = 7 \times 10^{34} \left(\frac{D}{7.2 \text{ kpc}}\right)^2 \text{ erg s}^{-1}\) (2–10 keV; Degenaar & Wijnands 2009). This is about three orders of magnitude lower than the maximum outburst luminosity exhibited by this source, yet still a factor \(\gtrsim 100\) above its quiescent level of \(L_X \sim 10^{32} \left(\frac{D}{7.2 \text{ kpc}}\right)^2 \text{ erg s}^{-1}\) (2–8 keV; Muno et al. 2003a). The source region is covered by one of our XMM-Newton observations on 2006 September 8, which is just before the subluminous outburst detected by Swift/XRT. During these observations, GRS 1741–2853 is not detected and we can infer a \(2\sigma\) upper limit on the PN count rate of \(\lesssim 0.003 \text{ counts s}^{-1}\). Using Table 7.3, we can estimate that the 2–10 keV luminosity of GRS 1741–2853 was \(\lesssim 3 \times 10^{32} \left(\frac{D}{7.2 \text{ kpc}}\right)^2 \text{ erg s}^{-1}\) at that time. Thus, one week prior to the peculiar short 2006 outburst there were no indications of enhanced activity above the quiescent level.

We note that GRS 1741–2853 underwent a new outburst, lasting \(\sim 4 \sim 5\) weeks and reaching up to \(L_X = 1 \times 10^{37} \left(\frac{D}{7.2 \text{ kpc}}\right)^2 \text{ erg s}^{-1}\), between 2009 September–November (Degenaar & Wijnands 2009). In 2010 late-July the source is again reported active displaying a 2–10 keV luminosity of \(\sim 4 \times 10^{35} \left(\frac{D}{7.2 \text{ kpc}}\right)^2 \text{ erg s}^{-1}\) (Degenaar et al. 2010b).

### 7.4.2  XMM J174457–2850.3

XMM J174457–2850.3 is an unclassified X-ray transient that was first detected in outburst in 2001 (Sakano et al. 2005) and has been seen active on numerous occasions since (Wijnands et al. 2006a; Muno et al. 2007b; Degenaar & Wijnands 2009, 2010; Degenaar et al. 2010b). Its quiescent 2–10 keV luminosity is \(\sim 10^{32} \text{ erg s}^{-1}\) (Sakano et al. 2005). Strikingly, this source is often found at luminosities of \(\sim 10^{33-34} \text{ erg s}^{-1}\), whereas it has been detected in a brighter state \(L_X \sim 10^{36} \text{ erg s}^{-1}\) only occasionally (2–10 keV; Degenaar & Wijnands 2010).

We detect activity from XMM J174457–2850.3 on several occasions during our
monitoring campaign. The position inferred from our observations is consistent with the coordinates listed by Muno et al. (2009), but not more accurate. As reported by Wijnands et al. (2006a), XMM J174457–2850.3 was active both during the HRC observations performed on 2005 June 5 (see also Wijnands et al. 2005a) and the ACIS follow-up pointing carried out on July 1. The 2–10 keV luminosities inferred from these observations are \( \sim 8 \times 10^{35} \) and \( \sim 3 \times 10^{33} \) erg s\(^{-1}\), respectively (assuming \( D = 8 \) kpc), indicating that the intensity decayed 2 orders of magnitude in 4 weeks. The source is again seen active in XMM-Newton data obtained in 2006 February and September, as well as during the series of ACIS pointings performed in 2007 March–May and XMM-Newton observations carried out in 2007 September (see Table 7.3). On these occasions the source is detected at 2–10 keV luminosities in the range of \( L_X \sim (1 - 9) \times 10^{33} \) erg s\(^{-1}\). XMM J174457–2850.3 is not detected during the other epochs of our campaign (i.e., 2005 October, 2007 July and 2008 March/July/September), but the inferred upper limits are comparable to the actual detections (\( L_X \lesssim (2 - 9) \times 10^{33} \) erg s\(^{-1}\); see Figure 7.6).

This object is so faint that most of our observations collect only \( \sim 20 - 30 \) source photons, prohibiting accurate spectral modelling. We fit only the spectral data obtained from the observations with the highest number of photons detected (Chandra/ACIS observations 6603 and 6605 yielded \( \sim 50 - 60 \) source photons each). Since the hydrogen column density remains unconstrained when left to vary freely, we fix this parameter to the value inferred from Swift/XRT data (\( N_H = 7.5 \times 10^{22} \) cm\(^{-2}\); Degenaar & Wijnands 2010). This results in powerlaw indices of \( \Gamma = 1.3 \pm 1.0 \) and \( 1.7 \pm 1.1 \) for the ACIS observations performed on 2007 March 12 and April 30, respectively. Within the errors, this is consistent with results obtained in other works (Sakano et al. 2002; Wijnands et al. 2006a; Degenaar & Wijnands 2010). For the remaining observations we convert the detected count rates into 2–10 keV unabsorbed fluxes adopting the above mentioned hydrogen absorption column density and a photon index of 1.5 (see Table 7.3). The spectrum extracted from the Chandra/ACIS observation performed on 2007 April 30 is plotted in Figure 7.2.

Swift observations uncovered a relatively bright outburst from XMM J174457–2850.3 in 2008 late-June, peaking at a 2–10 keV luminosity of \( 1 \times 10^{36} \) erg s\(^{-1}\) during the first observation that the source was in FOV (2008 June 28; Degenaar & Wijnands 2010). The source intensity was observed to decline to a level of \( L_X \sim 5 \times 10^{33} \) erg s\(^{-1}\) within one week. The Swift/GC monitoring observations did not cover source region before the outburst peak, leaving the duration of this relatively bright (\( L_X \gtrsim 10^{34} \) erg s\(^{-1}\)) episode unconstrained (Degenaar & Wijnands 2010). Since the source is not detected in our Chandra/HRC data obtained on 2008 May 10, yielding an upper limit on the 2–10 keV luminosity of \( \sim 8 \times 10^{33} \) erg s\(^{-1}\), we can infer that the luminous phase seen by Swift/XRT must have had a duration of
< 49 days (< 7 weeks). In 2010 late-July Swift/XRT observations again witness XMM J174457–2850.3 exhibiting a relatively bright episode with a 2–10 keV luminosity of \( \sim 1 \times 10^{35} \text{ erg s}^{-1} \) (Degenaar et al. 2010b).

### 7.4.3 AX J1745.6–2901

A third transient that is frequently detected during our monitoring campaign is located at an angular distance of \( \sim 1.5' \) from Sgr A*, at a position consistent with the Chandra localisation of AX J1745.6–2901 (Heinke et al. 2008). This neutron star LMXB, discovered in 1993 by the ASCA observatory, exhibits type-I X-ray bursts and its lightcurve displays eclipses that recur every \( \sim 8.4 \text{ h} \) and allow for the unambiguous determination of the orbital period of the binary (Maeda et al. 1996; Kennea & Skinner 1996). Following the detections by ASCA in 1993 and 1994, AX J1745.6–2901 was never reported in outburst again until 2006, despite extensive monitoring of the source region (see Section 7.1).

This transient is first detected in outburst during our XMM-Newton observations performed on 2006 February 27, displaying a luminosity of \( 4.6 \times 10^{35} \text{ erg s}^{-1} \) (2–10 keV and assuming a distance of \( D = 8 \text{ kpc} \)). In the subsequent observation performed on 2006 September 8, the source is not detected with an upper limit of \( L_X \lesssim 3 \times 10^{33} \text{ erg s}^{-1} \) (assuming a hydrogen column density of \( 21.8 \times 10^{22} \text{ cm}^{-2} \) and powerlaw index of 2.0; see Table 7.3). This is consistent with results from Swift/XRT observations of the GC, which indicated that the source was active between 2006 February and June, but resided in quiescence thereafter (Degenaar & Wijnands 2009).

It is unclear when the 2006 outburst of AX J1745.6–2901 started, since the position of the Sun with respect to the GC renders this region unobservable each year between November and February. However, the source was not detected during our 2005 monitoring observations, which implies that the outburst must have started after 2005 October 20 (see Table 7.1). The time span between the Chandra observations and the first detection of AX J1745.6–2901 on 2006 February 24 (with Swift; Kennea et al. 2006c) is 4 months, which constrains the outburst duration to be 3–7 months.

Renewed activity of the source was reported in 2007 February, as seen by various instruments (Kuulkers et al. 2007a; Wijnands et al. 2007; Porquet et al. 2007; Degenaar & Wijnands 2009). AX J1745.6–2901 is detected at similar intensity levels of \( L_X \sim (1 - 4) \times 10^{36} \text{ erg s}^{-1} \) during all our monitoring observations carried out between 2007 February and 2008 May (see Table 7.3). During the 2008 July observation, the source intensity had decreased by nearly a factor 10 and it went undetected in 2008 September, indicating that the source had returned to the quiescent state after a \( \sim 1.5 \text{-year long outburst} \) (see Figure 7.6). The Swift/XRT observations of the GC also suggest that AX J1745.6–2901 was continuously active since 2007 February, until it returned to quiescence in 2008 early-September (Degenaar & Wijnands 2010).
The long 2007–2008 outburst from AX J1745.6–2901 was a factor $\sim 5$ more luminous than the shorter 2006 outburst (see Table 7.3 and Figure 7.6, see also Degenaar & Wijnands 2010). We note that AX J1745.6–2901 is again reported active in 2010, displaying a similar luminosity as observed in 2006 (Degenaar et al. 2010b,c).

In the Chandra/HRC data obtained on 2008 May 10 we detect an X-ray flare from AX J1745.6–2901 that lasts for $\sim 50$ s (see the left plot in Figure 7.3). The fast rise and exponential decay shape, combined with the fact that this source is a known X-ray burster, strongly suggest that this event was a type-I X-ray burst, although we lack a spectral conformation due to the poor energy resolution of the HRC. Using the hydrogen column density found from fitting spectral data (see Table 7.3) and assuming a blackbody temperature typically seen for type-I X-ray bursts ($kT_{bb} = 2 - 3$ keV), the observed HRC peak count rate translates into a 0.01–100 keV luminosity of $\sim 5 \times 10^{37}$ erg s$^{-1}$. The duration of the flare matches other thermonuclear bursts detected from AX J1745.6–2901 (Maeda et al. 1996; Degenaar & Wijnands 2009).

The Chandra/ACIS-I observations performed on 2007 April 6 reveal an eclipse from this system with a duration of $\sim 1400$ s. The source remains to be detected within this interval at a count rate that equals $1/4$ of the out-of-eclipse emission (see right panel of Figure 7.3). This matches the description of the eclipses seen from this source by ASCA (Maeda et al. 1996). Other authors also report on eclipses with similar characteristics as seen during XMM-Newton and Chandra observations.
carried out on 2007 March–April and 2008 May, respectively, leaving no doubt that the X-ray transient detected in 2006–2008 is AX J1745.6–2901 (Porquet et al. 2007; Heinke et al. 2008).

Both the Chandra/ACIS and the XMM-Newton data obtained during the 2007–2008 outburst of AX J1745.6–2901 are subject to pile-up. We attempted to circumvent the expected effect on spectral shape and source flux by extracting source event from an annular region with a radius of \(r \sim 10^{−40}''\) for both data sets (see Sections 7.3.1 and 7.3.2). A simultaneous fit to the Chandra and XMM-Newton spectra results in a hydrogen column density of \(N_H = (21.8 \pm 0.3) \times 10^{22} \text{ cm}^{-2}\). Figure 7.2 displays the XMM-Newton/PN spectra of the 2006 February and 2008 March observations, which represent the two different outbursts of the source. We converted upper limits and HRC-I count rates into unabsorbed 2–10 keV fluxes using the above mentioned hydrogen column density and a powerlaw index of \(\Gamma = 2.0\) (see Table 7.3).

7.4.4 CXOGC J174535.5–290124

Close to AX J1745.6–2901, separated by only \(\sim 14''\), lies the unclassified X-ray transient CXOGC J174535.5–290124, which was discovered during Chandra monitoring observations of the GC (Muno et al. 2003b). This source is frequently detected at 2–10 keV luminosities of \(\sim 10^{33–34} \text{ erg s}^{-1}\) (for \(D = 8 \text{ kpc}\); Muno et al. 2005b; Wijnands et al. 2005c, 2006b; Degenaar et al. 2008a; Degenaar & Wijnands 2009), whereas its quiescent level is constrained to be \(L_X \lesssim 9 \times 10^{30} \text{ erg s}^{-1}\) (2–8 keV; Muno et al. 2005b).

Due to the close proximity of the two X-ray sources (see Figure 7.1), neither Swift nor XMM-Newton can spatially resolve AX J1745.6–2901 and CXOGC J174535.5–290124 when the former is active, because its relatively bright outbursts completely outshine CXOGC J174535.5–290124 (see Degenaar & Wijnands 2010). However, the Chandra instruments do provide the spatial resolution required to separate the two transients.

CXOGC J174535.5–290124 is active in our Chandra observations performed in 2005 October (HRC; Wijnands et al. 2005c), between 2007 March–May (ACIS), as well as in 2008 May and July (both HRC pointings; Degenaar et al. 2008b). As discussed in Section 7.4.3, AX J1745.6–2901 resided in quiescence during our XMM-Newton observations performed in 2006 and 2008 September. On both occasions we detect activity from CXOGC J174535.5–290124 (see also Wijnands et al. 2006b). For spectral fitting, we use only the XMM-Newton spectra since AX J1745.6–2901 was not active at that time and thus excludes contamination from this nearby source. The simultaneous fit (using both PN and MOS data) results a hydrogen column density of \(N_H = (30.4 \pm 8.6) \times 10^{22} \text{ cm}^{-2}\) and powerlaw indices of \(\Gamma = 1.7 – 2.5\) (see Table 7.3), yielding comparable 2–10 keV luminosities of \((1.9 – 2.4) \times 10^{34} \text{ erg s}^{-1}\).

Figure 7.2 shows the XMM-Newton/PN spectrum obtained on 2006 September 8.
We converted count rates and upper limits into 2–10 keV unabsorbed fluxes using the spectral parameters inferred from fitting the XMM-Newton data (see Table 7.3). The long-term lightcurve of CXOGC J174535.5–290124 obtained during our campaign is displayed Figure 7.6. This plot is suggestive of the source exhibiting two different outbursts, although the upper limits inferred from our observations in case of a non-detection are actually close to the level of activity displayed by the source. This makes it difficult to constrain the outburst and quiescent time scales. Swift/XRT monitoring observations of the GC suggest that CXOGC J174535.5–290124 was continuously active between 2006 July–November (when AX J1745.6–2901 resided in quiescence) and from 2008 September till October, whereas the source is not detected during the entire sample of 2009 observations (Degenaar & Wijnands 2010), nor in 2010. However, AX J1745.6–2901 became active again in 2010 June, depriving us of a view of CXOGC J174535.5–290124 (Degenaar et al. 2010c).

7.4.5 KS 1741–293

Our monitoring campaign detects activity from a transient X-ray source in field GC-7 during XMM-Newton observations obtained on 2007 September 6 and Chandra/HRC pointings performed on 2008 May 10 and July 16. As reported by Degenaar et al. (2008b), the source location inferred from our Chandra observations coincides with that of CXOGC J174451.6–292042, a transient X-ray source included in the catalogue of Muno et al. (2009). This source represents the Chandra counterpart of the neutron star LMXB KS 1741–293, which was discovered in 1989 August by the X-ray wide field camera TT M onboard the Mir space station (e.g., in 't Zand et al. 1991). At that time, the source displayed two type-I X-ray bursts, which revealed its binary nature and testified to the presence of a neutron star. KS 1741–293 was again detected with BeppoSAX in 1998 March (Sidoli et al. 2001a) and with ASCA in 1998 September (Sakano et al. 2002), displaying 2–10 keV luminosities of $\sim 10^{35} – 36$ erg s$^{-1}$ on both occasions (assuming $D = 8$ kpc). It is likely that these two observations caught the same outburst from the source, which thus had a duration of several months.

More recently, KS 1741–293 was serendipitously observed with Chandra in 2005 July, at a 2–10 keV luminosity of $\sim 1 \times 10^{36}$ erg s$^{-1}$ (Degenaar et al. 2008b). Around the same time, Integral bulge scan observations detected hard X-ray activity from the source between 2005 August–September (Kuulkers et al. 2007c). KS 1741–293 was also detected in outburst by Integral in 2003 March, as well as 2004 March, during

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5We note that Martí et al. (2007) tentatively associated KS 1741–293 with a different object appearing in the Chandra source catalogue (CXOGC J174451.0–292116 from Muno et al. 2006). However, as argued by Degenaar et al. (2008b) the long-term flux history and spectral properties strongly favour CXOGC J174451.6–292042 as the Chandra counterpart of KS 1741–293.
which two type-I X-ray bursts were observed (de Cesare et al. 2007).

We obtained a source spectrum from XMM-Newton data obtained on 2007 September 6 (see Figure 7.2). KS 1741–293 is faint enough not to cause pile-up in the EPIC instruments. The spectral data can be adequately fit with an absorbed power-law model with \( N_H = (16.6 \pm 1.8) \times 10^{22} \) cm\(^{-2} \) and photon index \( \Gamma = 1.8 \pm 0.3 \). The resulting 2–10 keV luminosity is \( 1.4 \times 10^{35} \) erg s\(^{-1} \). Subsequent XMM-Newton observations carried out on 2008 March 4 did not detect KS 1741–293, with an upper limit on the PN count rate of \( \lesssim 0.003 \) counts s\(^{-1} \). Using the spectral parameters given above, we can infer an upper limit on the 2–10 keV quiescent luminosity of \( \lesssim 6 \times 10^{32} \) erg s\(^{-1} \), which demonstrates that the outburst had ended by this time.

We searched through the Swift data archive in an attempt to constrain the duration of the 2007 outburst of KS 1741–293. The source is in FOV during a number of pointings performed between 2007 May 23 and August 9. A total of 55 observations were carried out during this episode with an accumulated exposure time of 57 ks. Examination of the Swift data reveals that KS 1741–293 resided in quiescence for the larger part of this epoch, albeit it exhibited enhanced activity during a short, 4-day interval between 2007 June 11–15, when the source intensity rose to \( L_X \sim 3 \times 10^{34} \) erg s\(^{-1} \) (Degenaar & Wijnands in prep.). The source is not detected in composite images both before (total exposure of \( \sim 10 \) ks) and after \( (t_{\text{exp}} \sim 43 \) ks) these dates. The above considerations suggest that the 2007 outburst of KS 1741–293 was confined within an interval between 2007 August 9 and 2008 March 4, implying a duration of \( \lesssim 6 \) months. There is an interesting similarity between the short, subluminous outburst observed from KS 1741–293, and a 1-week period of enhanced X-ray activity that was detected from the neutron star LMXB GRS 1741–2853 \( \sim 5 \) months before it started a mayor outburst (Degenaar & Wijnands 2009). The mini-outburst of KS 1741–293 occurred 1-2 months before the source erupted in a brighter outburst.

Our campaign detected renewed activity from KS 1741–293 during the Chandra/HRC observations carried out on 2008 May 10 (Degenaar et al. 2008b) and July 16 (see Figure 7.6). Using the spectral parameters reported in Table 7.3, the observed HRC count rates can be translated into 2–10 keV luminosities of \( 1 \times 10^{35} \) and \( 1 \times 10^{36} \) erg s\(^{-1} \), respectively. We obtained a number of Swift/XRT ToO follow-up observations spread \( \sim 2 \) weeks apart to constrain the properties of this outburst (e.g., the duration and total energy output; Degenaar & Wijnands 2008, Degenaar & Wijnands in prep.). These observations suggest that the source remained active for approximately 4 more months following the HRC detection of 2008 May, but that it returned to quiescence between 2008 August 21 and September 4. The average 2–10 keV luminosity inferred from the Swift observations is \( \sim 10^{35} \) erg s\(^{-1} \), peaking at \( \sim 2 \times 10^{36} \) erg s\(^{-1} \) (Degenaar & Wijnands in prep.). Integral observations revealed a new accretion outburst in 2010 March (Chenevez et al. 2010).
7.4.6 SAX J1747.0–2853

On three occasions, our monitoring observations detect activity from the transient LMXB SAX J1747.0–2853. This source was discovered with BeppoSAX in 1998 and its neutron star nature has been established by detection of type-I X-ray bursts (in ’t Zand et al. 1998; Sidoli et al. 1999). The properties of type-I X-ray bursts exhibiting a photospheric radius expansion phase put the source at a distance of 6.7 kpc (Galloway et al. 2008a). Following its discovery, several accretion outbursts with 2–10 keV luminosities of \( \sim 10^{36–37} (D/7.6 \text{ kpc})^2 \text{ erg s}^{-1} \) were detected from the source, with different X-ray instruments (Wijnands et al. 2002c; Natalucci et al. 2004; Werner et al. 2004; Markwardt & Swank 2004; Deluit et al. 2004). An earlier outburst from the source, occurring in 1991, was found in archival data (Grebenev et al. 2002). Wijnands et al. (2002c) observed SAX J1747.0–2853 with Chandra in between two bright outburst and detected the system at a 0.5–10 keV luminosity of \( \sim 2 \times 10^{35} (D/7.6 \text{ kpc})^2 \text{ erg s}^{-1} \). Since this is well above the quiescent level typically found for neutron star systems, its transient nature was cast in doubt (Wijnands et al. 2002c). However, an apparent quenching of type-I X-ray bursts suggested that the accretion was suppressed at least during some intervals (Werner et al. 2004).

SAX J1747.0–2853 is detected in outburst during the HRC-I observations performed on 2005 October 20 (Wijnands et al. 2005b,c), as well as in XMM-Newton data obtained on 2006 February (Wijnands et al. 2006b) and September. Integral Galactic bulge monitoring observations detected hard X-ray activity from the source in 2005 October and 2006 February (Kuulkers et al. 2005; Chenevez et al. 2006). The source is not detected during Chandra/HRC observations carried out in 2007 July, from which we can estimate an upper limit on the 2–10 keV luminosity of \( \lesssim 3.7 \times 10^{34} \text{ erg s}^{-1} \), which indicates that the source activity had ceased by that time (see also Figure 7.6).\(^6\) If the source was continuously active between our monitoring observations of 2005 October and 2006 September, the outburst thus had a duration of \( \gtrsim 0.9 \text{ yr} \). However, non-detections in our data obtained in 2005 June and 2007 July constrain the duration of the active period to be \( \lesssim 2.1 \text{ yr} \) (see Figure 7.6).

SAX J1747.0–2853 was again reported active as seen during Integral bulge scan observations performed in 2007 October (Brandt et al. 2007). Swift follow-up observations carried out a few days later revealed renewed activity of SAX J1747.0–2853 in the softer X-ray band as well, since it was detected at a 2–10 keV luminosity of \( \sim 10^{36} (D/7.6 \text{ kpc})^2 \text{ erg s}^{-1} \) (Cackett & Miller 2007). The source region is not covered by our monitoring observations of 2007 September, but SAX J1747.0–2853 is not detected in XMM-Newton data obtained in 2008 March. Combined with the lack of activity found in our 2007 July observations, this suggests that this new out-

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\(^6\)We note that the field in which SAX J1747.0–2853 is closest to aimpoint, GC-3, was not observed in 2007 July, but during that epoch the source region is covered by the observations of GC-1.
7.4 Results

The X-ray burst had a duration of $\lesssim 0.6$ yr. In 2009 February, Integral detected an X-ray burst from SAX J1747.0–2853, indicating that the source was again active (Chenevez et al. 2009a). Follow-up Swift/XRT observations performed a few days later constrained the source luminosity to be $\sim 2 \times 10^{35} (D/7.6 \text{ kpc})^2 \text{ erg s}^{-1}$ at that time (2–10 keV; Campana et al. 2009).

We fitted the XMM-Newton spectra obtained in 2006 February and September to obtain source fluxes. The February observation contained two X-ray bursts (see below), which were removed from the data for the purpose of fitting the persistent emission. A simultaneous fit to the two spectra yields a hydrogen column density of $N_H = (9.5 \pm 0.2) \times 10^{22} \text{ cm}^{-2}$ and powerlaw indices of $\Gamma = 2.0 \pm 0.1$ and $2.6 \pm 0.1$ (see Table 7.3). The inferred 2–10 keV luminosities for the 2006 February and September observations are $2.1 \times 10^{36}$ and $6.0 \times 10^{35} (D/7.6 \text{ kpc})^2 \text{ erg s}^{-1}$, respectively. The PN spectrum of the 2006 February observation is shown in Figure 7.2. Using $N_H = 9.5 \times 10^{22} \text{ cm}^{-2}$ and a powerlaw index of $\Gamma = 2.6$, we can estimate a 2–10 keV luminosity of $\sim 6.7 \times 10^{35} (D/7.6 \text{ kpc})^2 \text{ erg s}^{-1}$ for the HRC-I observation of 2005 October. Upper limits for other epochs were computed using the same spectral shape and result in values of $L_X \lesssim (4 - 37) \times 10^{33} (D/7.6 \text{ kpc})^2 \text{ erg s}^{-1}$ (see Figure 7.6). This suggests a strongly reduced accretion power and confirms the transient nature of the source, suggested by (Werner et al. 2004).

The lightcurve extracted from the 2006 February XMM-Newton observation reveals a pair of type-I X-ray bursts, shown in Figure 7.4. The time elapsed between these two events is 230 s (3.8 min). The X-ray bursts show the typical fast rise, exponential decay shape and have similar durations ($\sim 40$ s) and peak count rates. The PN switched off during the bursts due to the high count rate, so that we could only use the MOS cameras for a spectral analysis. To avoid pile-up, events had to be extracted from an annulus with inner (outer) radius of 20″ (40″).

Limited by statistics, we cannot perform time-resolved spectroscopy and therefore we extracted the full-burst spectra ($\sim 40$ s). A spectrum obtained from an interval of 100 s preceding the first burst was used to serve as a background reference. We fit both bursts to an absorbed blackbody model with the hydrogen column density fixed to the value obtained from fitting the persistent emission ($N_H = 9.5 \times 10^{22} \text{ cm}^{-2}$). For the first X-ray burst this yields a blackbody temperature of $kT_{bb} = 1.8 \pm 0.4$ keV and $R_{bb} = 5.2 \pm 0.9$ km. For the second burst we obtain comparable values of $kT_{bb} = 1.4 \pm 0.3$ keV and emitting region $R_{bb} = 7.4 \pm 1.0$ km. The spectra of both bursts are shown in Figure 7.5.

Extrapolation of the blackbody fits to the energy range of 0.01–100 keV, yields an estimate of the bolometric luminosity during the bursts of $L_{bol} \sim 3.6 \times 10^{37}$ and $3.1 \times 10^{37} (D/7.6 \text{ kpc})^2 \text{ erg s}^{-1}$ for the first and second burst, respectively. Using the count rate to flux conversion factor inferred from fitting the average burst spectra we can
Figure 7.4: XMM-Newton/EPIC-MOS2 5-s bin lightcurves of SAX J1747.0–2853 during the observation obtained on 2006 February 27 (0.5–12 keV energy band). The top image shows an interval of ~400 s during which two type-I X-ray bursts occurred. The bottom plots show the lightcurves of the individual bursts.
7.4 Results

roughly estimate that the bolometric peak luminosities of both bursts were $\sim 1.0 \times 10^{38} \left(\frac{D}{7.6 \text{ kpc}}\right)^2 \text{ erg s}^{-1}$, which is close to the Eddington limit for neutron stars. The persistent emission observed around the time of the bursts was approximately 1% of the Eddington rate (see Table 7.3).

7.4.7 GRO J1744–28

During all our XMM-Newton observations we detect a weak X-ray source consistent with the Chandra localisation of the transient neutron star LMXB GRO J1744–28 (Muno et al. 2009), which was discovered in 1995 with the BATSE aboard the Compton Gamma Ray Observatory (Fishman et al. 1995). Its neutron star nature was established by the detection of coherent X-ray pulsations with a frequency of 2.1 Hz, which allowed to determine the orbital period of the binary to be 11.8 days (Finger et al. 1996). Mayor outbursts reaching 2–10 keV luminosities of $\sim 10^{37–38} \text{ erg s}^{-1}$ were observed in 1995 and 1996 (for $D = 8 \text{ kpc}$, Woods et al. 1999). The source has been observed in quiescence at a 0.5–10 keV luminosity of $\sim (2 – 4) \times 10^{33} \text{ erg s}^{-1}$ (Daigne et al. 2002; Wijnands & Wang 2002), but enhanced activity a factor of a few above the quiescent level has also been reported (Muno et al. 2007b).

For the spectral fits we omitted the XMM-Newton observation obtained in 2006 September, because of the low number of photons collected. Using an absorbed powerlaw model to fit all data simultaneously, we obtain $N_H = (9.4 \pm 3.0) \times 10^{22} \text{ cm}^{-2}$ and powerlaw indices of $\Gamma = 2.5 – 3.2$ (see Table 7.3). The inferred 2–10 keV luminosities of the first 4 observations lie between $(1.5 – 6.5) \times 10^{33} \text{ erg s}^{-1}$, whereas the final observation indicates an enhanced intensity above the quiescent level with $L_X = 1.9 \times 10^{34} \text{ erg s}^{-1}$ (see Figure 7.6). The PN spectra obtained from the observations carried out in 2008 March and September are shown in Figure 7.2 for

Figure 7.5: XMM-Newton/PN spectra of the two type-I X-ray bursts observed from SAX J1747.0–2853 on 2006 February 26.
The Chandra/XMM-Newton monitoring campaign of the Galactic centre

comparison. Although GRO J1744–28 is not found in the Chandra/HRC images by running the wavdetect routine, it can be spotted by eye in the images of 2005 October and 2008 May. The source is close to the detection of our HRC observations, and the obtained upper limits are of similar magnitude as the actual detections (see Figure 7.6). The HRC-I count rates and upper limits were converted to 2–10 keV fluxes and luminosities using $N_H = 9.4 \times 10^{22} \text{cm}^{-2}$ and a powerlaw index of $\Gamma = 2.8$.

With the exception of the last observation, the luminosities inferred from fitting the XMM-Newton spectral data are similar to what has been found for GRO J1744–28 in quiescence (Wijnands & Wang 2002). Since (non-pulsating) neutron star LMXBs in quiescence often display a thermal spectrum (e.g., Bildsten & Rutledge 2001), we also fitted a blackbody model to the spectral data. Excluding the last observation that hinted enhanced activity, we find $N_H = (5.9 \pm 2.7) \times 10^{22} \text{cm}^{-2}$ and blackbody temperatures of $kT_{bb} = 1.0 \pm 0.3$ keV for the remaining three XMM-Newton spectra (yielding $\chi^2$ = 0.86 for 40 d.o.f.). This is unusually high for quiescent neutron stars, that are typically characterised by blackbody temperatures of $kT_{bb} \sim 0.2 - 0.3$ keV (e.g., Bildsten & Rutledge 2001). The corresponding emitting radii inferred for GRO J1744–28 are on the order of $R_{bb} \sim 0.1$ km. Similar results were obtained by previous authors and the mechanism responsible for the quiescent emission observed from GRO J1744–28 is therefore a subject of debate (Daigne et al. 2002; Wijnands & Wang 2002).

7.4.8 CXOGC J174541.0–290014

During the Chandra/HRC observations performed in 2005 October, we detect activity from CXOGC J174541.0–290014 (Wijnands et al. 2005c), an unclassified X-ray transient discovered during Chandra observations of the GC (Muno et al. 2003b). Between 1999 and 2005, this source was detected multiple times, displaying luminosities of a few times $10^{33}$ erg s$^{-1}$, whereas an upper limit on the quiescent level of $L_X \lesssim 8 \times 10^{31}$ erg s$^{-1}$ was inferred (2–8 keV energy band, assuming $D = 8$ kpc; Muno et al. 2005b). Using the spectral parameters reported by Muno et al. (2004), $N_H = 18.8 \times 10^{22} \text{cm}^{-2}$ and $\Gamma = 2.0$, we can convert the HRC count rate into a 2–10 keV luminosity of $1.2 \times 10^{34}$ erg s$^{-1}$. CXOGC J174541.0–290014 was detected only once during our campaign. From the observations performed at other epochs we can infer upper limits on the source luminosity of $\lesssim (0.5 - 5) \times 10^{33}$ erg s$^{-1}$ (2–10 keV; see Figure 7.6).

7.4.9 AX J1742.6–2901

During the final series of Chandra/HRC observations, performed in 2008 July, we detect an X-ray source located at $\alpha = 17^{h}42^{m}42.58^{s}$, $\delta = -29^\circ02'04.8''$ (J2000)
with an uncertainty of 1.5″. This position is coincident with that of AX J1742.6–2901, an unclassified X-ray source discovered during ASCA observations of the GC performed in 1998 September (Sakano et al. 2002). The ASCA source was tentatively associated with the ROSAT object 2RXP J174241.8–290215, which was detected at a count rate of $(1.9 \pm 0.3) \times 10^{-2}$ counts s$^{-1}$ during a 2 ks PSPC observation performed in 1992 March. The position derived from our Chandra observations is consistent with ROSAT localisation.

AX J1742.6–2901 is detected only once during our campaign, with a HRC-I count rate of $(6.8 \pm 2.5) \times 10^{-2}$ counts s$^{-1}$. The source is located just outside the FOV of our XMM-Newton pointings and was not covered by the Chandra survey of Muno et al. (2009). However, the source region was observed with Swift/XRT as part of a Swift follow-up program of ASCA sources with unknown nature (Degenaar et al. in prep.). During the XRT observations, performed on 2008 March 7 (i.e., 4 months prior to our Chandra/HRC detection), a single X-ray source was detected within the XRT FOV. The coordinates inferred from the Swift data coincides with the position determined from our Chandra/HRC observations.

The Swift/XRT spectrum can be fit with an absorbed powerlaw with hydrogen column density $N_H = 0.7^{+2.5}_{-0.7} \text{ cm}^{-2}$ and photon index $\Gamma = 2.1 \pm 1.5$. Assuming a distance of 8 kpc, the resulting unabsorbed 2–10 keV luminosity is $5.7 \times 10^{33} \text{ erg s}^{-1}$. Using these spectral parameters, the Chandra/HRC-I and ROSAT/PSPC count rates translate into 2–10 keV unabsorbed luminosities of $7.2 \times 10^{33}$ and $2.3 \times 10^{33} \text{ erg s}^{-1}$, respectively. Sakano et al. (2002) report an unabsorbed luminosity of $5.3 \times 10^{33} \text{ erg s}^{-1}$ (0.7–10 keV), as detected during the ASCA observations. Since AX J1742.6–2901 has been detected at such comparable intensity levels with ROSAT (1992), ASCA (1998), Swift and Chandra (both 2008), and given the fact that the source is close to the detection limit of our HRC observations (see Figure 7.6), it seems plausible that the source is not an X-ray transient but rather a weak persistent source that displays a factor of a few variability.

### 7.4.10 Previously unidentified source in XMM-Newton data

In all XMM-Newton observations covering the field GC-6, we detect an X-ray source at a $\alpha = 17^h46^m54.15^s$, $\delta = -29^\circ15'42.6''$ (J2000) with an uncertainty of 4′′. This object is only detected above 2 keV and we find no counterpart in the SIMBAD astronomical database or in DSS/2MASS images. The source region was not covered by the Chandra survey of Muno et al. (2009). We designate this new X-ray source XMMU 174654.1–291542. This object is not detected in the individual HRC-I exposures, although it appears when merging all Chandra data together. This allows

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7The second ROSAT source catalogue of pointed observations (2RXP) is available at http://www.mpe.mpg.de/xray/wave/rosat/gra.
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for a refined position of $\alpha = 17^h46^m54.47^s$, $\delta = -29^\circ15^\prime44.0^\prime\prime$ (J2000) with an uncertainty of 1.5''.

We simultaneously fit all XMM-Newton spectra to an absorbed powerlaw, which yields $N_H = (5.2 \pm 1.2) \times 10^{22}$ cm$^{-2}$ and photon indices varying between $\Gamma = 0.3 - 1.8$ (see Table 7.3), suggesting significant variations between the different spectra. This is also illustrated by Figure 7.2, which displays the PN spectra obtained in 2006 September and 2008 May. When the spectra are fitted individually, we obtain a considerable spread in hydrogen column densities ($N_H = (1.6 - 9.0) \times 10^{22}$ cm$^{-2}$) and powerlaw indices ($\Gamma = 0.1 - 1.8$), although the errors on both parameters are large. We also fitted the spectra simultaneously with the powerlaw index tied between the different observations, whereas the hydrogen column density was left to vary. This resulted in a photon index of $\Gamma = 1.0 \pm 0.3$ and hydrogen column densities ranging between $N_H = (2.5 - 10.2) \times 10^{22}$ cm$^{-2}$, with typical errors of $\sim 2.0 \times 10^{22}$ cm$^{-2}$ (for $\chi^2 = 1.04$ for 159 d.o.f.). Regardless of the chosen approach, we obtain luminosities lying in a range of $\sim (0.7 - 3.0) \times 10^{34}$ erg s$^{-1}$ (assuming a source distance of 8 kpc). For the individual HRC-I observations we obtain upper limits in the range $\lesssim (4 - 7) \times 10^{33}$ erg s$^{-1}$. In the merged HRC image, the source is weakly detected at a count rate of 0.003 $\pm$ 0.001 counts s$^{-1}$. For $N_H = 5.2 \times 10^{22}$ cm$^{-2}$ and $\Gamma = 1.0$, this implies a 2–10 keV luminosity of $6.3 \times 10^{33}$ erg s$^{-1}$. Given the small difference between the XMM-Newton detections and the Chandra upper limits, we cannot assess whether this object is truly transient or rather a persistent source that displays intensity variations by a factor of a few (see Figure 7.6).

We searched archival data to shed more light on the long-term variability of this newly identified X-ray source. XMMU J174554.1–291542 was in FOV of the GC survey carried out by ASCA (Sakano et al. 2002). The limiting sensitivity of that campaign was comparable to the level of activity we detect for XMMU J174554.1–291542 during our observations. Furthermore, we find two Chandra/ACIS pointings that cover the source region, carried out on 2006 November 2 and 2008 May 10 (obs ID 7163 and 9559, the exposure times are $\sim 14.3$ and $\sim 14.8$ ks, respectively). During both observations XMMU J174554.1–291542 is one of the brightest objects in the field. Conversion of the extracted ACIS count rates using the spectral parameters listed in Table 7.3 yields a luminosity of $\sim 10^{34}$ erg s$^{-1}$ for both observations, which is similar to the level we detect during our campaign. This could point towards a persistent nature, although all observations lie within a time range of $\sim 2.5$ yr and we cannot exclude the possibility that the source underwent a long outburst.

7.4.11 Possible transient reported by Wijnands et al. (2006a)

Wijnands et al. (2006a) reported on the detection of a possible new very-faint X-ray transient, that was found only during our HRC-I observation of 2005 June 5, at a
7.5 Discussion

rate of $\sim 0.008$ counts s$^{-1}$. This object is detected in the XMM-Newton observations carried out in 2008 September at a count rate of $\sim (1.9 \pm 0.1) \times 10^{-2}$ counts s$^{-1}$, whereas the other XMM-Newton observations yield 2$\sigma$ count rate upper limits of $\leq 0.7 \times 10^{-2}$ counts s$^{-1}$. This indeed indicates a possible transient nature. However, the XMM-Newton observations indicate that this source is detected only in the 0.5–2 keV band, with no photons in the harder 2–12 keV band. It is therefore not a candidate X-ray binary.

7.5 Discussion

We have presented the results of 4 years of monitoring data of the GC with the Chandra and XMM-Newton observatories. We have covered a field of 1.2 square degree around Sgr A*, that was targeted on 10 different epochs between 2005 June and 2008 September. Our study focussed on the behaviour of transient X-ray sources located in this region that reach 2–10 keV peak luminosities $\gtrsim 1 \times 10^{34}$ erg s$^{-1}$ when in outburst. We detected activity of 8 previously known X-ray transients during our campaign. On average, 6 of these were active each year (see Table 7.3). We discussed the X-ray spectra and long-term lightcurves for the detected transients. All except AX J1742.6–2901 (see below) are highly absorbed ($N_H \gtrsim 5 \times 10^{22}$ cm$^{-2}$), indicating source distances close to or beyond the Galactic centre.

We detect type-I X-ray bursts from both AX J1745.6–2901 and SAX J1747.0–2853. For the latter, we find a pair of a type-I X-ray bursts that have a waiting time (recurrence time) of 3.8 min (see Section 7.5.4). Furthermore, during several observations SAX J1747.0–2853 is not detected with upper limits on the source luminosity of a few times $10^{33} \left( \frac{D}{6.7 \text{ kpc}} \right)^2$ erg s$^{-1}$, which testifies its classification as transient X-ray source (cf. Wijnands et al. 2002c; Werner et al. 2004). For AX J1745.6–2901 we also detect a $\sim 1400$ s long eclipse in the X-ray lightcurve during one of our observations, consistent with the eclipse properties seen during ASCA observations (Maeda et al. 1996).

In addition to the above mentioned transient systems, we detect two weak unclassified X-ray sources that, despite being undetected at some epochs during our campaign, are likely persistent. The first of these is AX J1742.6–2901, which has also been observed with ROSAT, ASCA and Swift at similar intensity levels as found during our observations. From the Chandra/HRC data we obtained an improved position for the source. The hydrogen absorption column density inferred from fitting Swift/XRT spectral ($N_H \sim 0.7 \times 10^{22}$ cm$^{-2}$) is considerably lower than inferred for the other X-ray sources in our survey, which indicates that it is likely located at a distance $< 8$ kpc. Furthermore, we detect a previously unknown X-ray source, which we designate XMMU J174554.1–291542. This object was detected in all individual
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*XMM-Newton* observations as well as in the merged *Chandra*/HRC image. Inspection of archival data suggests that this XMMU J174554.1–291542 is likely persistent at a luminosity of \( \sim 10^{34} \text{ erg s}^{-1} \) (assuming a distance of 8 kpc). Despite its apparent steady X-ray luminosity, we detect significant changes in the source spectrum on a time scale of months. These can be attributed to variations in either the hydrogen absorption column density or the powerlaw spectral index.

### 7.5.1 The population of Galactic centre X-ray transients

In Table 7.4 we list all known X-ray transients that are located in the region covered by our campaign. This table is an update from Wijnands et al. (2006a), where we have included two new transients that were discovered by *Swift* in 2006 (Degenaar & Wijnands 2009). Whereas most sources remain unclassified, there are 6 confirmed LMXBs of which 5 contain a neutron star primary, as testified by the detection of X-ray pulsations (GRO J1744–28) or type-I X-ray bursts (GRS 1741–2853, AX J1745.6–2901, KS 1741–293 and SAX J1747.0–2853). The fifth LMXB, CXOGC J174540.0–290031, has an orbital period of 7.9 h that has been inferred from the detection of eclipses in the X-ray lightcurve. This source has been suggested to harbour a black hole based on the detection of strong radio emission (Muno et al. 2005a; Porquet et al. 2005a).

Out of the 16 transients listed in Table 7.4, we have detected 8 in an active state during our campaign. Moreover, extensive monitoring of the GC region during the past decade has shown that 10 transients (i.e., 63%) recurred between 1999 and 2010 (see fourth column in this table), 6 of which even experienced three or more distinct outbursts during this epoch (these are the neutron star transients GRS 1741–2853, AX J1745.6–2901, KS 1741–293 and SAX J1747.0–2853, and the unclassified transients CXOGC J174535.5–290124 and XMM J174457–2850.3). The fact that no new X-ray transients with peak luminosities \( \gtrsim 1 \times 10^{34} \text{ erg s}^{-1} \) were found during our campaign confirms suggestions from previous authors that the majority of sources that recur on time scales less than a decade and undergo outbursts of at least a few days have now been identified in this region (in’t Zand et al. 2004; Muno et al. 2009; Degenaar & Wijnands 2010). The last new discoveries date back to 2006 (Degenaar & Wijnands 2009).

### 7.5.2 Low-level accretion activity

As discussed in Sections 7.4.1 and 7.4.5, both GRS 1741–2853 and KS 1741–293 have shown short, weak outbursts (\( \tau_{\text{ob}} \lesssim 1 \) week and \( L_X \lesssim 10^{34–35} \text{ erg s}^{-1} \)) that were preceding longer and brighter accretion episodes (duration of several weeks/months with 2–10 keV luminosities peaking at \( \sim 10^{36–37} \text{ erg s}^{-1} \)). Albeit on a different scale,
one can argue that AX J1745.6–2901 displayed something similar: a mayor outburst with a 2–10 keV peak luminosity of $6 \times 10^{36}$ erg s$^{-1}$ was detected from this system in 2007–2008, whereas a few months earlier (in 2006) it underwent an accretion episode that had a duration and intensity that were both a factor $\sim 5$ lower.

Looking at Figure 7.6, which displays the long-term lightcurves obtained for the 10 different sources studied in this work, it is striking that several objects appear active at levels of $\sim 10^{33–34}$ erg s$^{-1}$ without necessarily becoming brighter. Although XMM J174457–2850.3, GRO J1744–28 and SAX J1747.0–2853 are known to exhibit outburst episodes with luminosities equalling or exceeding $10^{36}$ erg s$^{-1}$, all three systems spend long times at much lower intensity levels that are yet enhanced compared to the quiescent state (for the former two see Figure 7.6; for SAX J1747.0–2853 see Wijnands et al. 2002c). While upper limits on the quiescent luminosity leave no doubt on the transients nature (Muno et al. 2005b), both CXOGC J174535.5–290124 and CXOGC J174541.0–290014 have never been observed at 2–10 keV luminosities exceeding $\sim 10^{34}$ erg s$^{-1}$ and several other sources also remain well below $L_X = 10^{36}$ erg s$^{-1}$ (see Table 7.4).

All of the above examples demonstrate that accretion can continue at low X-ray luminosities of $\sim 10^{33–35}$ erg s$^{-1}$ (2–10 keV). Such low, quasi-stable accretion episodes are hard to accommodate within the disc instability model, which is believed to drive transient outbursts in LMXBs.

### 7.5.3 Ultra-faint transients

While the present work focussed on transient X-ray sources with luminosities $\gtrsim 1 \times 10^{34}$ erg s$^{-1}$, our campaign also detected a number of objects that appear variable by a factor of $\gtrsim 5–10$ but remain below $\sim 5 \times 10^{33}$ erg s$^{-1}$ (assuming $D = 8$ kpc). We found several of such sources in our *XMM-Newton* observations, that are hard (most photons emitted above 2 keV) and for which no DSS/2MASS counterparts are found, which effectively rules out that these are foreground active stars. Two such examples are CXOGC J174451.7–285308 and CXOGC J174423.4–291741 from the *Chandra* catalogue of Muno et al. (2009). Both objects were detected once during our campaign at 2–10 keV luminosities of $\sim 3 \times 10^{33}$ erg s$^{-1}$. CXOGC J174451.7–285308 is indicated by Muno et al. (2009) as exhibiting long-term variability by a factor of $\sim 70$. CXOGC J174423.4–291741, on the other hand, is listed in this catalogue as a weak persistent source displaying a luminosity of $\sim 10^{32}$ erg s$^{-1}$ (using the conversion factor from photon to energy flux quoted by these authors).

As discussed in Section 7.5.2, several confirmed and candidate X-ray binaries display activity at similar intensity levels. Furthermore, Heinke et al. (2009a) find a transient object with a peak luminosity of $\sim 6 \times 10^{33}$ erg s$^{-1}$ in the globular cluster M-15, that can likely be identified as a neutron star X-ray binary. This suggests...
that there could be X-ray binaries amongst these 'ultra-faint transients' found in our XMM-Newton data, although a significant fraction might be accreting white dwarfs (Verbunt et al. 1997). The properties of the ultra-faint transients will be the subject of further study.

7.5.4 The X-ray burst pair of SAX J1747.0–2853

In our XMM-Newton observation performed on 2006 February 27, we detect two consecutive type-I X-ray bursts from SAX J1747.0–2853, separated by only 3.8 min. Such a recurrence time is amongst the shortest measured for type-I X-ray burst pairs. Other bursts with similarly short recurrence times were reported from the neutron star LMXBs 4U 1705–44 (3.8 min; Keek et al. 2010), 4U 1636–536 (5.4 min; Linares et al. 2009a), 4U 1608–52 (4.3–6.4 min; Galloway et al. 2008a) and EXO 0748–676 (6.5 min; Boirin et al. 2007; Galloway et al. 2008a). Furthermore, SAS-3 detected a series of three X-ray bursts with waiting times of $\sim 17$ and $\sim 4$ min, originating from a source close to the Galactic centre (Lewin et al. 1976). However, due to source confusion it could not be confirmed that all three bursts originated from the same object.

Thermonuclear X-ray bursts repeating within minutes represent a challenge to our understanding of burst physics. Current theoretical models predict that over 90% of the accreted hydrogen/helium is burned during a type-I X-ray bursts, and implies that it would take at least a few hours to accumulate enough matter to power a new burst (Woosley et al. 2004). This is at odds with the detection of X-ray bursts that have short recurrence times and thus suggests that some of the initial fuel is preserved after ignition of the first burst (Galloway et al. 2008a; Keek et al. 2010). One possible explanation for the occurrence of burst pairs could be that the matter is confined to certain parts of the neutron star surface, e.g., the magnetic poles, and that the bursts of a pair ignite at different locations. Alternatively, the bursts might ignite in separate layers, lying on top of each other. In this scenario first burst causes unburned fuel to be mixed down to larger depth, which can cause the ignition of a new burst (e.g., Keek et al. 2009).

A systematic study of a large number of short recurrence times bursts shows that, on average, the second burst a burst pair is less bright, cooler and less energetic than the first, although burst sequences of similar fluence are also observed (Boirin et al. 2007; Keek et al. 2010). Furthermore, for several sources the duration of the second burst was found to be shorter than the preceding one, suggestive of a reduced hydrogen content after the first burst has ignited. This would favour the explanation that the bursts are resulting from different envelope layers rather than different areas of the neutron star (Boirin et al. 2007; Keek et al. 2010). The two type-I X-ray bursts observed from SAX J1747.0–2853 were of similar duration ($\sim 40$ s) and also reached
similar peak luminosities (estimated to be close to the Eddington luminosity). Fitting the spectral data of the persistent emission shows that the source was accreting at \( \sim 1\% \) of the Eddington rate when the burst pair was observed. This is consistent with the findings of Keek et al. (2010), who show that bursts with recurrence times of \( \lesssim 40 \) min are seen for sources accreting at \( \lesssim 5\% \) of the Eddington rate.

We note that the bursts observed from SAX J1747.0–2853 contained within the RXTE catalogue of Galloway et al. (2008a) have recurrence times of hours. However, Keek et al. (2010) study an extended data sample, including bursts detected with BeppoSAX, and report on the detection of three burst pairs with short recurrence times from SAX J1747.0–2853 (compared to 57 single bursts). The time intervals between the bursts are not reported by these authors.

Acknowledgments
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Table 7.4: List of (confirmed) X-ray transients in the region covered by this campaign.

<table>
<thead>
<tr>
<th>Source name</th>
<th>Offset Sgr A* (&quot;)</th>
<th>$L_{\text{peak}}$</th>
<th>Comments</th>
<th>Repeat$^a$</th>
<th>Ref.$^b$</th>
</tr>
</thead>
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<tr>
<td>CXOGC J174540.0−290031</td>
<td>0.05</td>
<td>$1 \times 10^{35}$</td>
<td>obscured LMXB, radio source, $P_{\text{orb}} = 7.9$ h</td>
<td>N</td>
<td>1,2,3</td>
</tr>
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<td>2</td>
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<td>$2 \times 10^{35}$</td>
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<td>Y</td>
<td>2,4</td>
</tr>
<tr>
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<td>$2 \times 10^{35}$</td>
<td>unclassified</td>
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<td>2,5</td>
</tr>
<tr>
<td>1A 1742−289</td>
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<td>$7 \times 10^{38}$</td>
<td>radio source</td>
<td>N</td>
<td>6,7</td>
</tr>
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<td>CXOGC J174535.5−290124*</td>
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<td>$3 \times 10^{34}$</td>
<td>unclassified</td>
<td>Y</td>
<td>2,4,5</td>
</tr>
<tr>
<td>AX J1745.6−2901*</td>
<td>1.37</td>
<td>$6 \times 10^{36}$</td>
<td>neutron star LMXB (burster), $P_{\text{orb}} = 8.4$ h</td>
<td>Y</td>
<td>4,5,8</td>
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<td>Swift J174553.7−290347</td>
<td>4.50</td>
<td>$2 \times 10^{35}$</td>
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<td>$8 \times 10^{34}$</td>
<td>unclassified</td>
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<td>2</td>
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<td>GRS 1741−2853*</td>
<td>10.00</td>
<td>$1 \times 10^{37}$</td>
<td>neutron star LMXB (burster), $D = 7.2$ kpc</td>
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<td>4,5,9,10</td>
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<td>4</td>
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<td>unclassified</td>
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<td>11</td>
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<td>$5 \times 10^{36}$</td>
<td>neutron star LMXB (burster)</td>
<td>Y</td>
<td>17,18</td>
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Note.– Sources marked by an asterisks were active during our campaign. The 2–10 keV peak luminosities (in units of erg s$^{-1}$) assume a distance of 8 kpc unless indicated otherwise. $^a$ A positive indication implies that at least two distinct outbursts were observed between 1999–2010. $^b$ References: 1=Muno et al. (2005a), 2=Muno et al. (2005b), 3=Porquet et al. (2005a), 4=Degenaar & Wijnands (2009), 5=Degenaar & Wijnands (2010), 6=Davies et al. (1976), 7=Branduardi et al. (1976), 8=Maeda et al. (1996), 9=Muno et al. (2003a), 10=Trap et al. (2009), 11=Sakano et al. (2005), 12=Werner et al. (2004), 13=Wijnands et al. (2002c), 14=Giles et al. (1996), 15=Wijnands & Wang (2002), 16=Daigne et al. (2002), 17=in ’t Zand et al. (1991), 18=de Cesare et al. (2007).
Figure 7.6: Luminosity history of the (candidate) transient X-ray binaries detected during our monitoring campaign. Squares (HRC) and bullets (ACIS) indicate *Chandra* measurements, whereas triangles refer to *XMM-Newton* observations. The upper limits represent a 2σ confidence level.
Figure 7.6: Continued.
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Figure 7.6: Continued.
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   – Chapter 2

   Multi-wavelength observations of 1RXH J173523.7–354013: revealing an unusual bursting neutron star
   – Chapter 4

   Further X-ray observations of EXO 0748–676 in quiescence: evidence for a cooling neutron star crust
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    *Swift/XRT follow-up observation of the field of XTE J1719–291*

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*XMMSL1 J171900.4–353217 returns to quiescence*

*Swift/XRT detects new outbursts of the galactic centre X-ray transients GRS 1741–2853 and XMM J174457–2850.3*

*Swift/XRT follow-up and a refined position of the X-ray transient XTE J1728–295*

*Candidate optical counterparts of XTE J1728–295 = IGR J17285–2922*
Samenvatting in het Nederlands

Het ontrafelen van de eigenschappen van zwakke röntgendubbelsterren

Compacte sterren: eindstadia van sterevolutie

Net zoals mensen op een zekere moment geboren worden en sterven, hebben ook sterren niet het oneindige leven. Sterren ontstaan in reusachtige moleculaire gaswolken, zoals bijvoorbeeld de Adelaarsnevel, die is afgebeeld in Figuur A. Het grootste deel van hun leven brengen ze door als zogenaamde hoofdreeksster, terwijl ze diep in hun binnenste waterstof verbranden. Deze levensfase, waarin onze zon zich op dit moment bevindt, duurt miljoenen tot miljarden jaren. Zodra alle waterstof is omgezet begint de ster helium te verbranden en zwelt deze op; dit wordt de reuzenfase genoemd. Met het verbranden van chemische elementen komt energie vrij, die tegenstrijdig levert aan de zwaartekracht en de ster zo behoedt voor instorten. Echter, wanneer de voorraad van verbrandingsmaterialen uitgeput is, barst een ster uit elkaar en gaat zo zijn laatste levenfase in; de ster is dan een zogenaamde compact object geworden.

Er bestaan drie soorten compacte objecten, te weten witte dwergen, neutronensterren en zwarte gaten. Welke van deze drie het eindstadium van een sterrenleven zal vormen hangt af van hoe zwaar een ster is bij zijn geboorte. De lichtste sterren, die niet veel zwaarder zijn dan onze zon, worden aan het einde van hun leven een witte dwerg; een object ter grootte van onze aarde, maar dan veel zwaarder, namelijk ongeveer net zo zwaar als onze zon. Zwaardere sterren daarentegen, zullen eindigen
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als neutronenster of zwart gat. De vorming van een neutronenster of zwart gat gaat niet onopgemerkt voorbij. Dit gebeurt namelijk in een supernova explosie, één van de meest energetische gebeurtenissen in het heelal, waarbij een enorme hoeveelheid energie en gas de ruimte in worden geblazen. Dit levert schitterende beelden op, zoals bijvoorbeeld te zien is in Figuur A. Dit proefschrift gaat over onderzoek naar neutronensterren en zwarte gaten, daarom zal in dit hoofdstuk verder niet worden ingegaan op witte dwergen.

Neutronensterren en zwarte gaten vormen de meest raadselachtige en fascinerende objecten in ons heelal. Wat ze zo bijzonder maakt is dat in deze hemellichamen heel veel massa in een klein volume is samengeperst. Zo hebben neutronensterren een massa van 1 tot 2 keer de massa van onze zon, maar al deze materie is samengeperst in een bol met een straal van slechts 10 kilometer (ter vergelijking: onze zon heeft een straal van bijna 1 miljoen kilometer). Om je een voorstelling te kunnen maken van deze indrukwekkende dichtheid; als we alle mensen op de wereld (dat zijn er ruim 6 miljard) zouden samenpersen in een luciferdoosje, zou de materie net zo dicht op elkaar geperst zijn als in een neutronenster het geval is. Anders gezegd: een theelepelje materie van een neutronenster zou grofweg zo’n 5000 miljard kilogram wegen! Daarbij hebben neutronensterren ook nog eens een zeer hoog magneetveld, dat ieder magneetveld dat in aardse laboratoria kan worden geproduceerd ver te bo-
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ven gaat. Het is eenvoudig voor te stellen dat onder zulke omstandigheden de materie zich heel anders gedraagt dan wij hier op aarde gewend zijn. Het is daarom voor wetenschappers interessant om te weten hoe de interne samenstelling en structuur van een neutronenster eruit ziet, omdat dit tot meer inzicht kan leiden in het fundamenteel gedrag van de materie waaruit ons heelal is opgebouwd. Neutronensterren vormen dus natuurlijke laboratoria voor extreme omstandigheden die we niet op aarde kunnen nabootsen.

Zwarte gaten zijn nog een stapje extremer dan neutronensterren en deze objecten hebben de meest sterke zwaartekracht die we tegenkomen in het heelal. Om te kunnen ontsnappen aan de zwaartekracht van een hemellichaam heb je een bepaalde snelheid nodig; als wij vanaf de aarde een raket de ruimte in willen sturen vereist dit een snelheid van zo’n 11 kilometer per seconde (dat is 40 duizend kilometer per uur). De zon heeft een sterker zwaartekrachtsveld dan de aarde en daar zou in een vergelijkbare situatie een snelheid van 600 kilometer per seconde nodig zijn. Nu zou in het geval van een zwart gat een snelheid van minstens 300 duizend kilometer per seconde vereist zijn om te kunnen ontsnappen aan het immense zwaartekrachtsveld! Dit is sneller dan de snelheid waarmee licht beweegt en daarom zal niets, zelfs geen licht, kunnen ontsnappen. Een dergelijk object is dus letterlijk ‘zwart’. In tegenstelling tot een neutronenster, kunnen we daarom geen informatie verkrijgen over het ‘binnenste’ van een zwart gat. Echter, door de omstandigheden rondom een zwart gat te studeren kunnen we theorieën die zwaartekracht beschrijven, zoals de algemene relativiteitstheorie van Einstein, onder de meest extreme omstandigheden testen.

Röntgendubbelsterren: effecten van immense zwaartekracht

In tegenstelling tot onze zon, welke een geïsoleerde ster is, zijn de meeste sterren die we in het heelal waarnemen onderdeel van een meervoudig systeem, dat bestaat uit twee of meer sterren, die bij elkaar worden gehouden door de zwaartekracht. Sommige van deze meervoudige systemen zijn dubbelstersystemen, bestaande uit twee sterren die zo dicht bij elkaar staan dat zij elkaars evolutie drastisch kunnen beïnvloeden. Wanneer één van de sterren een supernova explosie heeft ondergaan, waarbij een neutronenster of zwart gat wordt gevormd en het dubbelstersysteem ondanks deze ca-

8Niets kan sneller dan het licht bewegen. Licht beweegt zich echter niet oneindig snel voort, maar reist met een snelheid van 300 duizend kilometer per seconde (in vacuum). Omdat afstanden in het heelal zo onmetelijk groot zijn doet het licht er dus een bepaalde tijd over om ons te bereiken. Zo duurt het ongeveer 8 minuten voordat het licht dat wordt uitgezonden door de zon de aarde bereikt: het licht heeft dan een afstand van zo’n 150 miljoen kilometer afgelegd. De meest dichtbijzijnde ster, Proxima Centauri, staat op dermate grote afstand dat licht er 4.2 jaar over doet om ons te bereiken. Dit betekent dat we elk astronomisch object zien zoals dit er in het verleden uitzag, namelijk op het moment dat het licht werd uitgezonden, maar inmiddels kan de ster dus al aanzienlijk veranderd zijn (misschien is deze inmiddels al ontploft in een supernova explosie!). We kijken dus altijd terug in de tijd.
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Figuur B: Schematische weergave van een röntgendubbelster waarin overdracht van massa plaatsvindt. Deze figuur is gemaakt met behulp van de RNSIM software van R. Hynes.


Helaas voor astronomen wordt röntgenstraling geabsorbeerd door de aardatmosfeer. Dit is maar goed ook, want anders zou leven op aarde onmogelijk zijn, aangezien röntgenstraling het DNA in cellen beschadigt. Gelukkig maakten technische ontwikkelingen het halverwege de 20e eeuw mogelijk om röntgen-detectie instrumenten buiten de aardatmosfeer te brengen, aan boord van raketten en satellieten. Daarmee was de röntgensterrenkunde geboren. Figuur C geeft een schematische weergave van de satellieten, die hedentendage om onze aarde bewegen (dit zijn overigens niet al-
Figuur C: Deze afbeelding is een computersimulatie van alle objecten die door mensen in een baan om de aarde zijn gebracht. De eerste onbemande satelliet was de *Spoetnik*, die in 1957 werd gelanceerd en ongeveer 3 maanden om de aarde draaide. Velen volgden sindsdien. Deze afbeelding is gebaseerd op echte data: er zijn vele duizenden objecten bekend die rond de aarde cirkelen. De meeste bewegen op zo’n 1000 kilometer hoogte en zijn satellieten van commerciële, militaire of wetenschappelijke aard. Op die hoogte kunnen brokstukken tientallen jaren rondzwerven voordat ze opbranden in de atmosfeer. Van dit grote aantal apparaten zijn er momenteel maar enkele honderden werkzaam. Bronvermelding: *European Space Agency ESA*.

lemaal röntgensatellieten). Tijdens mijn promotieonderzoek heb ik intensief gebruik gemaakt van 3 van deze satellieten, genaamd *Chandra*, *XMM-Newton* en *Swift*. De waarnemingen die een satelliet maakt worden naar de aarde gestuurd en vervolgens op de computer geanalyseerd. Het licht dat een röntgendubbelster uitzendt kan worden onderzocht op variaties in de tijd, zowel op korte tijdschalen van milliseconden als veel langere tijdschalen van jaren. Daarnaast kan worden gekeken naar de energieverdeling van het licht, bijvoorbeeld of het licht voornamelijk bij hoge of juist bij lage energie wordt uitgezonden. Dit wordt *spectroscopie* genoemd. Door middel van deze technieken kunnen we de eigenschappen van het zwarte gat of de neutronenster (bijvoorbeeld de massa, of in het geval van een neutronenster ook de temperatuur), van de accretieschijf (bijvoorbeeld de grootte en temperatuur) en van de tweede ster (bijvoorbeeld of dit een zware of een lichte ster is) afleiden. Op deze manier proberen we onder andere te begrijpen hoe röntgendubbelsterren ontstaan en evolueren.

Voorbijgaande röntgenbronnen: ’aan’ en ’uit’
Het proces van materie-overdracht, waarbij een accretieschijf wordt gevormd en een dubbelster helder in röntgenstraling maakt, is niet altijd continu. Vaak wordt slechts
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Het mysterie van de zwakke röntgenbronnen
Het bestaan van röntgendubbelsterren is reeds bekend sinds de begindagen van de röntgenastronomie, zo’n 50 jaar geleden. Echter, pas in de laatste jaren, met de komst van gevoelige röntgensatellieten, is het mogelijk geworden om de eigenschap-
pen van deze objecten bij lage röntgenhelderheden te bestuderen. Dit heeft tal van interessante aspecten aan het licht gebracht, zoals bijvoorbeeld het afkoelen van neutronensterren nadat een einde is gekomen aan een hele lange (jaren tot tientallen jaren) röntgenuitbarsting. Dit wordt verder besproken in de volgende paragraaf. Ook is mede dankzij de huidige generatie van röntgensatellieten duidelijk geworden dat er een groep röntgendubbelsterren bestaat, die uitzonderlijk zwak zijn tijdens de fase van massa-overdracht; wel 10–1000 keer zwakker dan normaal wordt gezien voor röntgendubbelsterren. Het is nog een groot mysterie waarom deze röntgendubbelsterren veel minder röntgenstraling uitzenden. Eén van de mogelijkheden om de zwakke helderheid te verklaren is dat het dubbelsterren betreft, waarbij een neutronenster materie opslokt van een planeet in plaats van een normale ster. In een dergelijk geval is het een groot raadsel hoe de planeet de gewelddadige supernova-explosie waarin de neutronenster ontstond heeft overleefd, dus dit zou heel bijzonder zijn. Een manier om deze hypothese te testen is door het gedrag van de zwakke röntgendubbelsterren in detail te onderzoeken, bijvoorbeeld hoe lang ze ’uit’ zijn en hoeveel energie wordt uitgestraald tijdens perioden van massa-overdracht. In een gebied van ongeveer 1 graad rondom het centrum van onze Melkweg9 komen veel van deze zwakke röntgendubbelsterren voor (zie Figuur D) en dit gebied heb ik daarom ook uitvoerig bestudeerd tijdens mijn promotieonderzoek.

**Neutronensterren: extreme eigenschappen**

De algemene eigenschappen van een röntgendubbelster waarin zich een zwart gat bevindt zijn niet heel anders dan voor een röntgendubbelster die een neutronenster bevat. Er zijn echter twee waarneembare fenomenen die allebei de aanwezigheid van een neutronenster verraden: röntgenpulsaties en röntgenflitsen. Beide fenomenen hebben een vast oppervlak nodig hebben om te kunnen ontstaan en een zwart gat heeft dat (zeer waarschijnlijk) niet.

**Röntgenpulsaties**

Wanneer de neutronenster een sterk magneetveld heeft, is het mogelijk dat de accretiestroom wordt afgebogen en naar de magnetische polen van de neutronenster wordt geleid. Dit proces lijkt erg op wat er op onze planeet gebeurt, wanneer geladen zonneweeëltjes door het aardse magneetveld worden afgebogen in de richting van de

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9Het dynamische centrum van onze Melkweg is een supermassief zwart gat genaamd Sagittarius A*, welke een massa heeft van enkele miljarden malen de massa van de zon. Dit is veel zwaarder dan de zwarte gaten die in röntgendubbelsterren voorkomen: deze hebben een massa van enkele (tientallen) malen de massa van de zon. Men denkt dat in het centrum van vrijwel alle sterrenstelsels zich een supermassief zwart gat bevindt. Een gebied van ongeveer 1 graad rondom Sagittarius A* is hemelsbreed zo’n 200 parsec, waarbij een parsec een afstand van ongeveer dertigduizend miljard kilometer is.
magnetische polen, wat het spectaculaire fenomeen poollicht (ook wel noorderlicht) veroorzaakt. Echter, in een röntgendubbelster heeft het invallende gas een veel hogere energie en is het magneetveld vele malen krachtiger en daarom wordt de energie niet uitgezonden als zichtbaar licht, maar als röntgenstraling. Doordat een neutronenster ronddraait zal het licht, dat wordt uitgezonden vanaf de polen, voor een waarnemer op aarde periodiek te zien zijn. Dit is vergelijkbaar met hoe de stralen van een vuurtoren worden waargenomen, met een periode die afhankelijk van de draaisnelheid van de lamp. Neutronensterren waarvan op een dergelijke manier pulsaties van licht worden ontvangen worden daarom röntgenpulsars genoemd. Sommige röntgendubbelsterren vertonen pulsaties die zich slechts binnen enkele milliseconden herhalen. Dit betekent dat de neutronenster in 1 seconde wel honderden malen om zijn as draait! Andere neutronensterren draaien weer veel langzamer en doen er tientallen of zelfs honderden seconden over om één maal om hun as te wentelen. Door het nauwkeurig bestuderen van dergelijke röntgenpulsaties kan veel informatie worden gekregen over de röntgendubbelster, zoals bijvoorbeeld de tijd waarin de twee objecten om elkaar heen draaien en hun massaverhouding.

**Röntgenflitsen**

Een ander spectaculair fenomeen zijn röntgenflitsen. Wanneer het geaccreteerde gas zich ophoopt op het oppervlak van de neutronenster, kan het op een zeker moment een thermonucleaire kettingreactie op gang brengen. Bij een dergelijke geweldadige gebeurtenis komt binnen korte tijd een enorme hoeveelheid energie vrij. De meeste van dergelijke röntgenflitsen duren ongeveer 10 seconden en in die tijd wordt typisch een hoeveelheid energie van ongeveer $10^{32}$ Joule uitgezonden. Omdat een dergelijk astronomisch groot getal misschien niet zoveel zegt: bij een vernietigende atoombom komt zo'n $10^{17}$ Joule aan energie vrij. Tijdens een röntgenflits neemt de totale röntgenhelderheid van de röntgendubbelster grofweg een factor 100–1000 toe. Dit duurt meestal enkele seconden tot minuten, hoewel in uitzonderlijke gevallen een dergelijke röntgenflits wel uren of soms zelfs dagen kan duren. Terwijl de korte en meer gewone röntgenflitsen meerdere keren per dag kunnen voorkomen zijn de lange röntgenflitsen veel zeldzamer. De eigenschappen van röntgenflitsen kunnen belangrijk inzicht geven in de eigenschappen van het dubbelstersysteem, zoals bijvoorbeeld het type ster waarvan de neutronenster materie opslokt, alswel de interne eigenschappen van de neutronenster zelf. Zo wordt het moment van ontploffen mede bepaald door de temperatuur in het binnenste van de neutronenster, welke weer samenhangt met zijn samenstelling. Zoals eerder uitgelegd is dit één van de grote vraagstukken uit de sterrenkunde, dat wetenschappers graag willen ontrafelen omdat het ons inzicht kan verschaffen in het fundamenteel gedrag van materie onder extreme omstandigheden.
**Samenvatting in het Nederlands**

*Koelende neutronensterren: een kijkje in hun binnenste*

Tijdens de periode van massa-overdracht wordt vrijwel al het licht van een dubbelster (niet alleen de röntgenstraling, maar ook het zichtbare- en infrarood licht) gedominneerd door de accretieschijf. Tijdens deze fase kan dus het proces van accretie uitvoerig worden bestudeerd en kunnen mogelijk röntgenpulsaties en röntgenflitsen worden waargenomen. Wanneer de overdracht van materie uitgeschakeld, biedt dit weer andere mogelijkheden om de eigenschappen van het de röntgendubbelster te onderzoeken. Zo kunnen we zichtbaar- en infrarood licht van de donor-ster ontvangen en dit kan heel belangrijk zijn om te begrijpen wat voor ster dit precies is (bijvoorbeeld of de ster nog waterstof heeft en of het om een lichte of een zware ster gaat). Daarnaast is het ook mogelijk om röntgenstraling direct van het oppervlak van de neutronen-ster waar te nemen. Hierdoor kan worden onderzocht hoe het proces van accretie de eigenschappen van de neutronenster heeft beïnvloed. Zo blijkt dat het proces van massa-overdracht de neutronenster opwarmt, maar wanneer de accretie stopt zal de neutronenster weer afkoelen. Het afkoelen hangt in sterke mate af van de interne eigenschappen van de neutronenster en biedt dus de mogelijkheid om dit te studeren door met behulp van röntgensatellieten nauwkeurig te volgen hoe snel en tot welke temperatuur de neutronenster afkoelt. Dergelijk onderzoek vereist het gebruik van gevoelige röntgeninstrumentsen, omdat deze straling vele malen zwakker is dan van een accretieschijf. Het proces van afkoelen duurt typisch enkele jaren.

**De inhoud van dit proefschrift**

Tijdens mijn promotie heb ik verschillende aspecten van röntgendubbelsterren bestudeerd bij lage röntgenhelderheden. Daarvoor heb ik voornamelijk gebruik gemaakt van instrumenten aan boord van de satellieten *Chandra, XMM-Newton* en *Swift*. Bij al deze onderzoeken heb ik gebruik gemaakt van spectroscopie (dus het analyseren van de energieverdeling van het licht) om het gedrag van verschillende röntgendubbelsterren over een tijdschaal van jaren te studeren.

In het eerste deel van dit proefschrift, in hoofdstukken 2 en 3, onderzoek ik een röntgendubbelster waarin een neutronenster sinds 1984 continu massa van zijn begeleidende ster opslokte, maar daar in 2008 ineens mee ophield. Door deze röntgendubbelster, EXO 0748–676 genaamd, regelmatig waar te nemen met *Chandra, XMM-Newton* en *Swift*, bestuderen we hoe de temperatuur van de neutronenster verandert nu er geen massa meer wordt overgedragen. In de afgelopen 10 jaar is een dergelijk onderzoek slechts voor drie andere röntgendubbelsterren uitgevoerd en dat heeft ons inzicht in de interne eigenschappen van neutronensterren in belangrijke mate vergroot. Er zijn niet heel veel röntgendubbelsterren die we kunnen gebruiken om het afkoelen van neutronensterren te onderzoeken, dus we waren enorm enthousiast toen EXO 0748–676 in 2008 ‘uit’ bleek te gaan. Onze waarnemingen hebben
aangetoond dat de neutronenster in EXO 0748–676 zich anders gedraagt dan de drie andere röntgendubbelsterren. In de afgelopen twee jaar is de neutronenster namelijk aanzienlijk minder afgekoeld dan waargenomen voor de andere drie. Een mogelijke verklaring hiervoor is dat EXO 0748–676 relatief korte tijd 'uit' is (jaren tot enkele tientallen jaren), terwijl deze lange tijd 'aan' is (tientallen jaren). Op deze manier blijft de neutronenster waarschijnlijk relatief warm ten opzichte van neutronensterren in andere röntgendubbelsterren. We blijven deze neutronenster de komende jaren volgen met de satellieten Chandra, XMM-Newton en Swift om te testen of ons vermoeden juist is.

In hoofdstuk 4 staat een röntgendubbelster genaamd 1RXH J173523.7–354013 centraal, welke een uitzonderlijke röntgenflits van wel twee uur lang heeft vertoond. Deze röntgenbron was al ontdekt in 1990, maar het was nooit duidelijk geworden of dit een röntgendubbelster was (er zijn namelijk ook andere astronomische objecten die röntgenstraling uitzenden). De detectie van deze röntgenflits leverde echter het onomstotelijk bewijs dat 1RXH J173523.7–354013 een röntgendubbelster is, waarin zich een neutronenster bevindt. Bovendien zijn lange röntgenflitsen die zo lang duren zeer zeldzaam en we kunnen veel leren over de neutronenster door deze fenomenen te bestuderen. Door gebruik te maken van ultraviolet- en röntgenwaarnemingen met verschillende satellieten, zowel als waarnemingen op optische- (zichtbaar licht) en infrarood golflengten verkregen met telescopen hier op aarde, ontrafelen we de eigenschappen van deze röntgendubbelster. Een belangrijke conclusie van dit werk is dat de röntgendubbelster bestaat uit een neutronenster en een waterstofrijke donor-ster. Dit was een verrassende vinding, omdat de röntgeneigenschappen eigenlijk deden vermoeden dat de donor-ster geen waterstof (meer) zou hebben. Deze conclusie maakt het des te raadselachtiger dat de röntgendubbelster zo zwak is.

Ten slotte bespreken de hoofdstukken 5, 6, en 7 een groot aantal röntgenwaarnemingen van het centrum van onze Melkweg, verzameld tussen 2005 en 2009 met de satellieten Chandra, XMM-Newton en Swift. Omdat er veel zwakke voorbijgaande röntgenbronnen in dit gebied liggen bieden deze waarnemingen de uitgelezen mogelijkheid om het gedrag van deze vreemde objecten nauwkeurig te bestuderen. Door de röntgenuitbarstingen en tussenliggende rustperioden van de zwakke röntgenbronnen te onderzoeken, proberen we te testen of deze bronnen mogelijk bijzondere röntgendubbelsterren zijn. Bij dit onderzoek zijn twee nieuwe voorbijgaande (mogelijke) röntgendubbelsterren ontdekt. Deze bronnen hebben een naam gekregen die bestaat uit de satelliet waarmee ze zijn ontdekt (in dit geval Swift) en de coördinaten aan de hemel: Swift J174553.7–290347 en Swift J174622.1–290634. De locaties van deze twee nieuwe röntgenbronnen zijn aangegeven in Figuur D.
Dankwoord

Iedereen heeft recht
op een encounter.
De Grote Wijnstok

Het zit er op, het felbegeerde boekje is hier! Het waren vier fantastische jaren, ik heb met volle teugen genoten van het promoveren. Dat had in sterke mate te maken met de geweldige sfeer op en rond het Anton Pannekoek Instituut, maar ook vrienden en familie hebben een belangrijk aandeel gehad in het tot stand komen van mijn proefschrift. Dit is wellicht de enige keer in mijn leven dat ik een boek schrijf en daarom wil ik hier graag van de gelegenheid gebruik maken om mijn waardering uit te spreken voor diverse mensen.

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10Hoewel ik een co-autheurschap van 'Memoires van Voetbalvrouwen', uitgebracht onder het pseudoniem 'Debby van Dijk', niet onmogelijk acht.
verdient ook zeker een eervolle vermelding omdat je me in mijn vroege AIO dagen wegijs hebt gemaakt op API en in de röntgensterrenkunde. Het was niet alleen ontzettend gezellig om jouw kamergenoot te zijn (zo hebben we bijvoorbeeld heel veel lol gehad bij het maken van de opstelling met de fietsjes voor de open dag), maar ik heb ook veel van je geleerd over X-ray data-analyse en programmeren in perl. Dat zorgde voor een hele fijne start van mijn promotie.

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Dankwoord

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Nathalie Degenaar,
Amsterdam, oktober 2010
De antwoorden voor onderstaand kruiswoordraadsel zijn te vinden in mijn Nederlandse samenvatting.

Horizontaal
1. Object ter grootte van Amsterdam met een vergelijkbare massa als onze zon.
4. Engelse benaming voor een röntgendubbelster die 'aan' en 'uit' gaat.
5. Voorbeeld van een gebied waar veel nieuwe sterren ontstaan.
7. Benaming van de levensfase waarin onze zon zich op dit moment bevindt.
8. Satelliet vernoemd naar de Engelse wetenschapper die onder meer een klassieke beschrijving van de zwaartekracht formuleerde.
11. Naam van het supermassieve zwarte gat in het centrum van onze Melkweg.
14. Verzamelnaam voor de objecten die de eindfase in een sterrenleven vertegenwoordigen.
17. Hemellichaam waaraan niets, ook geen licht, kan ontsnappen.
18. Chemisch element dat sterren in hun binnenzonde verbranden tijdens de hoofdreeks.

Verticaal
2. Dubbelster waarin een neutronenster of een zwart gat materie oplokt van een normale ster.
3. Satelliet waarmee de afbeeldingen van de Adelaarsnevel en de Krabpulsar zijn gemaakt.
6. Techniek in de sterrenkunde waarbij onderzoek wordt gedaan naar de energieverdeling van licht.
10. Benaming voor een neutronenster waarvan we periodiek pulsen van licht ontvangen.
11. Explosie van een zware ster waarbij een zwart gat of een neutronenster wordt gevormd.
12. Engelse benaming voor een thermonucleaire explosie op het oppervlak van een neutronenster.
15. Wetenschappelijke benaming voor het proces van massa-overdracht in een röntgendubbelster.
16. Satelliet waarmee twee nieuwe voorbijgaande röntgenbronnen werden gevonden nabij het centrum van onze Melkweg.
OPLOSSING:

Onder de juiste inzendingen wordt een verrassing verloot.
Over de uitslag kan niet worden gecorrespondeerd.